Seminario del DCAIN

Offshore Measurements of Ocean Waves using Stereo Vision Systems

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Outline

- Motivation
- Prior vision-based systems for wave measurement
- Strategies to solve the reconstruction problem:
  - Disparity map (~depth map)
  - Wave-height (elevation) map
- Extension to space-time processing
- Conclusions

Motivation

- Topic: measurements of ocean waves using vision systems.
- Applications:
  - Monitoring of sea states
  - Improvement in the design of platforms
  - Study of turbulence and wave mechanics
  - Validation of physical models of the ocean
- Interdisciplinary work:

  ocean engineering and computer vision

Literature review

- Stereography and vision applied to ocean engineering:
  - First experiments: cameras mounted on a ship (Schumacher, 1939).
  - Long-wave sea topography (SWOP) (Coté et al. 1960).
  - Directional measurement of short ocean waves (Shemdin et al. 1988, 1992).

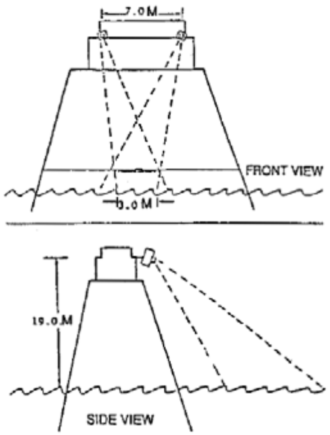


Figure 1. Schematic of Stereo Geometry Used in the Chesapeake Light Tower Experiment.

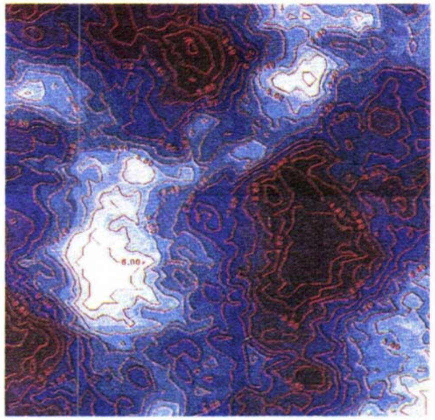


PLATE 1. Example contour map of ocean surface elevation. The surface area covered is 4.1 m by 4.1 m. The elevation contours are in cm.

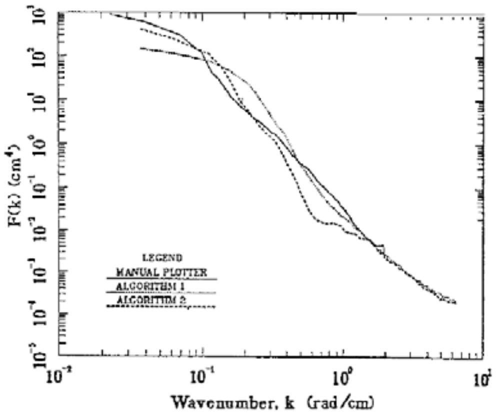
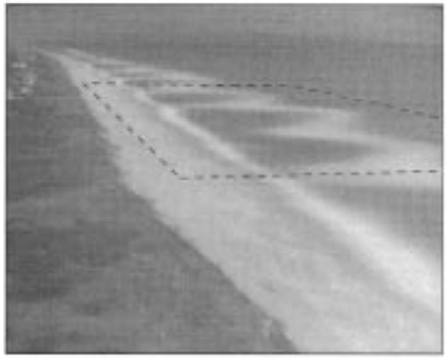


Figure 3. Comparison of Omni-Directional Spectra Using Two Digital Stereo-Correlation Algorithms and the Stereo Plotter Method.

Literature review

- Nearshore Oceanographic Field Studies (Holland et al. 1997)



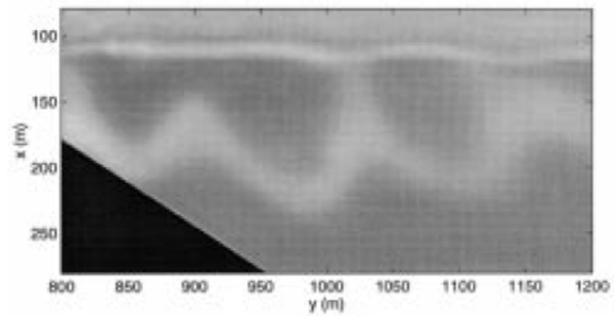
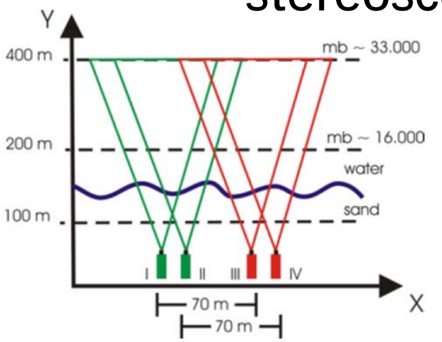
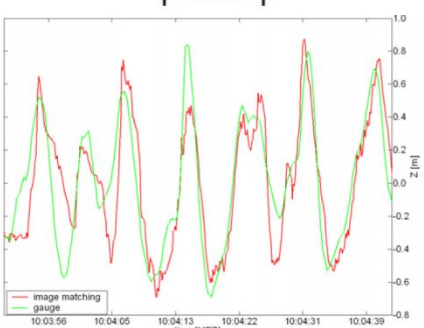


Fig. 5.   Ten-minute time exposure images of wave-breaking patterns at Duck,

- WaveScan project (Santel et al. 2004):
  stereoscopic 3d-image sequence analysis of sea surfaces.





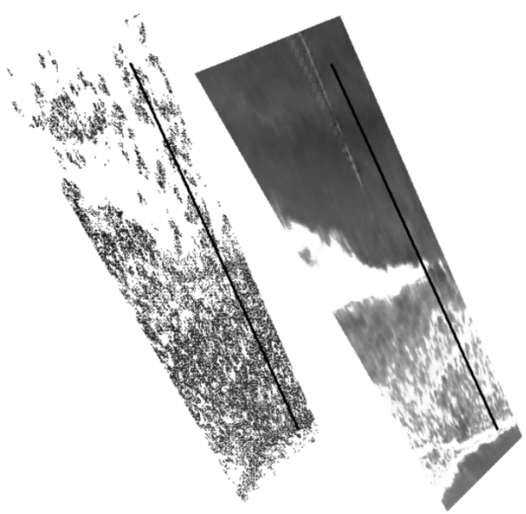


Figure 4. Correlated points and associated orthophoto

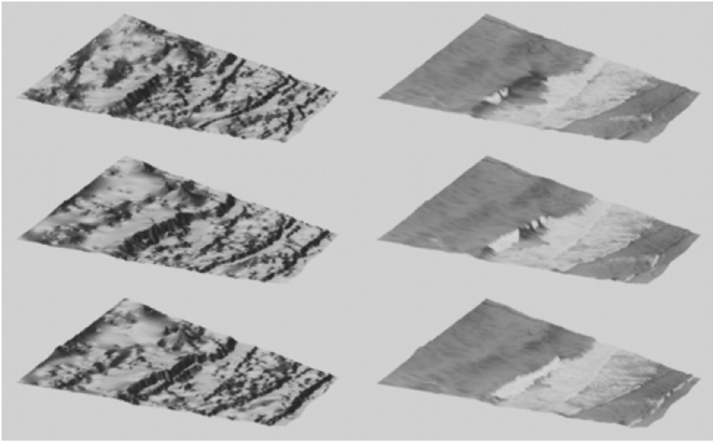
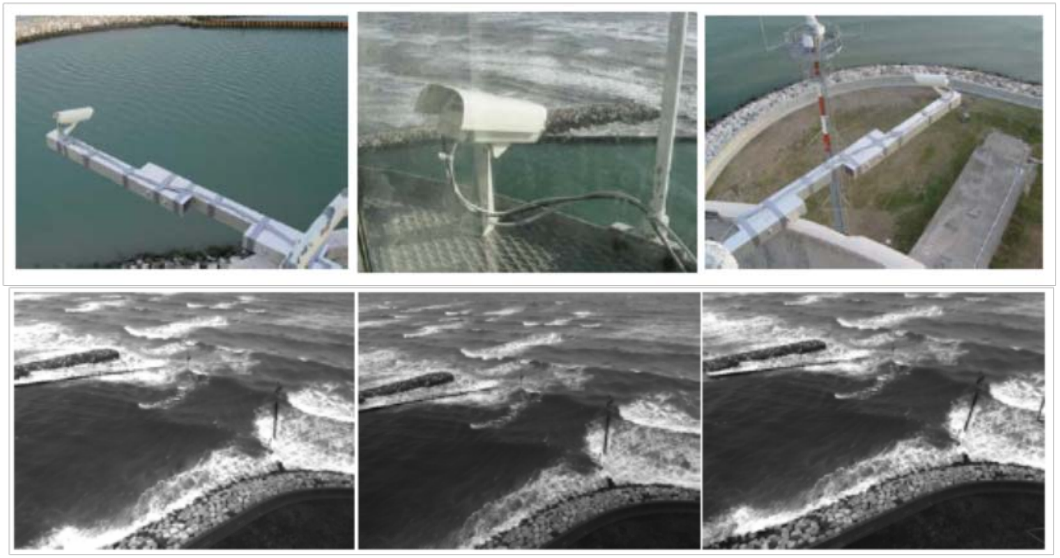


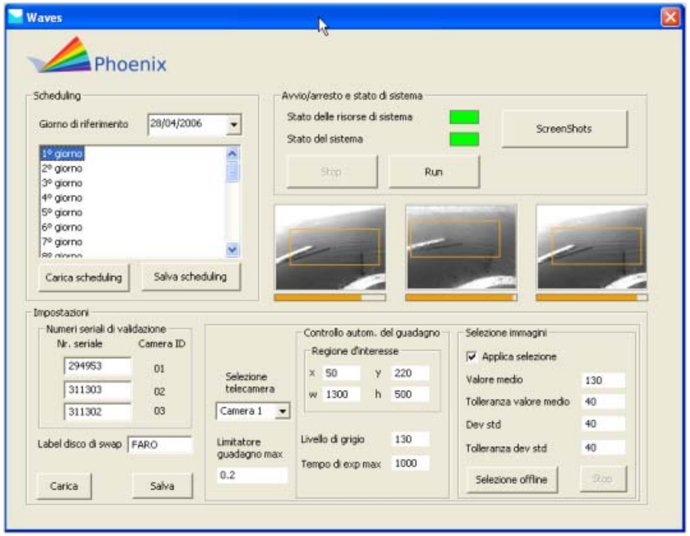
Figure 6. Sequence of water surfaces with Δt = 1 s
left: surface models; right: with overlaid orthophotos

Literature review. WASS (Benetazzo, 2006)

Goal: to study and predict ocean wave patterns from image sensors

- Image acquisition
(Bi/Trinocular synchronized and calibrated digital cameras)



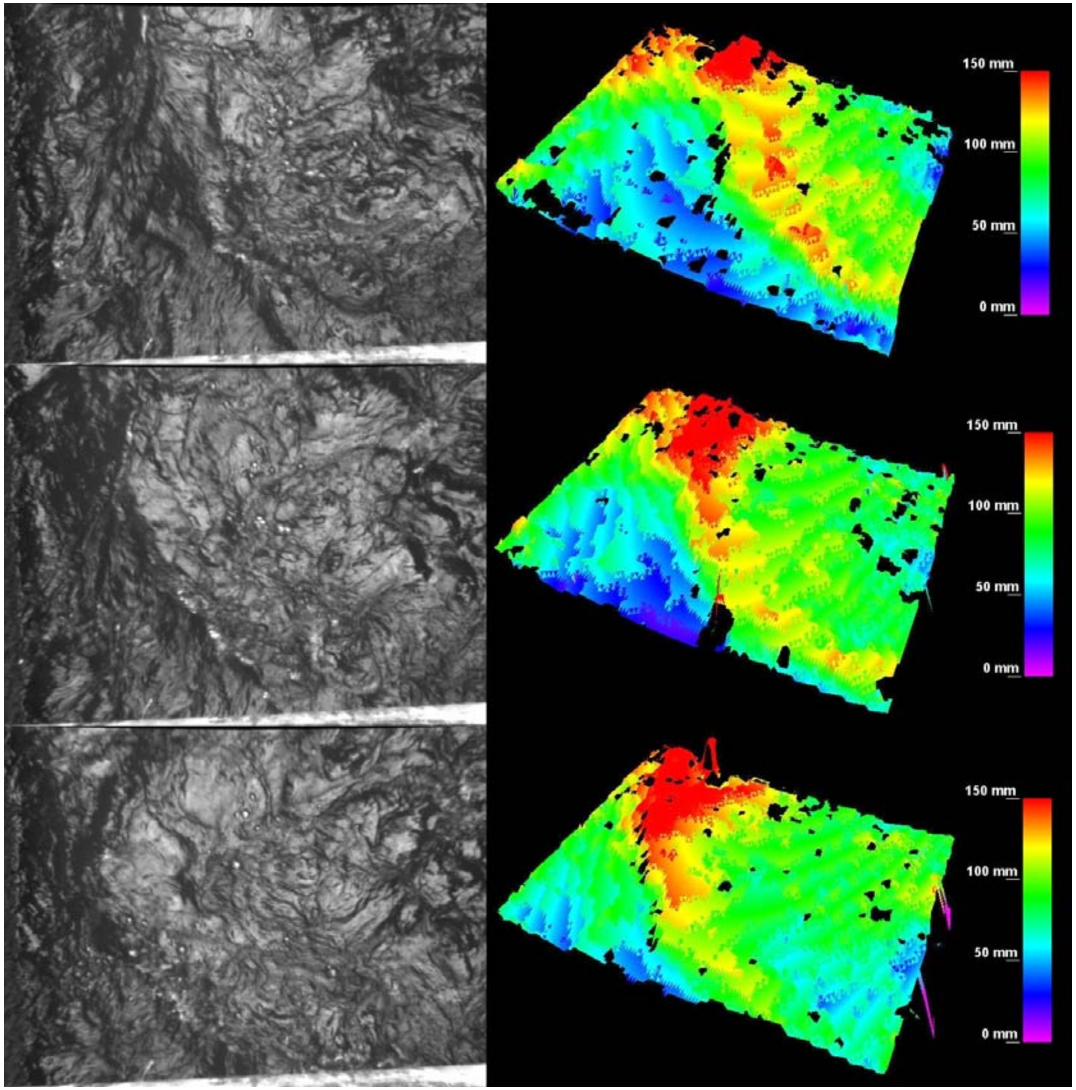


- Image processing
Reconstruct the surface of the water (epipolar stereo method)

Benetazzo, A. "Measurements of short water waves using stereo matched image sequences". *Coastal Engineering*, 53:1013-1032, 2006.

Literature review. WASS (Benetazzo, 2006)

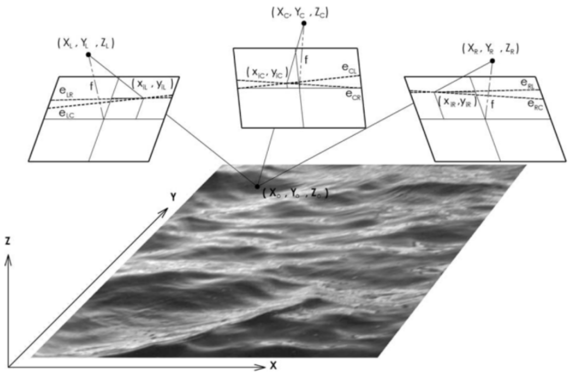
Water surface elevation in *time*:
from 2D image sequences to 3D map sequences

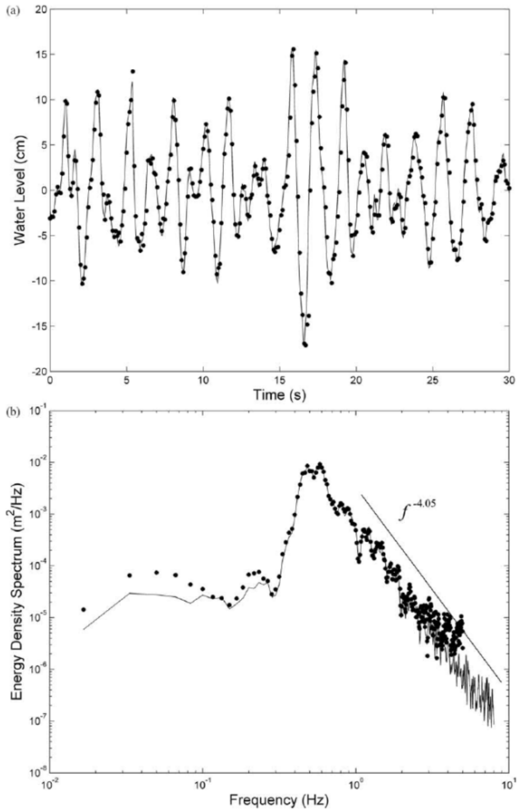


- Z_0 ~ 1.70 m, b = 0.22 m
- Matched Area : 0.94 x 0.78 m^2
- e_{rx} = e_{ry}= 0.15 cm, e_{rz} = 0.69 cm
- 90 % of points matched
- 480 x 640 pixel camera
- F = 6.3 mm, ss=1/200 s

Literature review. ATSIS

- Automatic Trinocular Stereo Imaging System (ATSIS) (Wanek and Wu, 2006).
- Measurement and analysis of ocean wave fields in 4D (MacHutchon and Liu, 2007, 2009).
- Virtual wave gauges for measuring surface wave characteristics (Bechle and Wu, 2011).





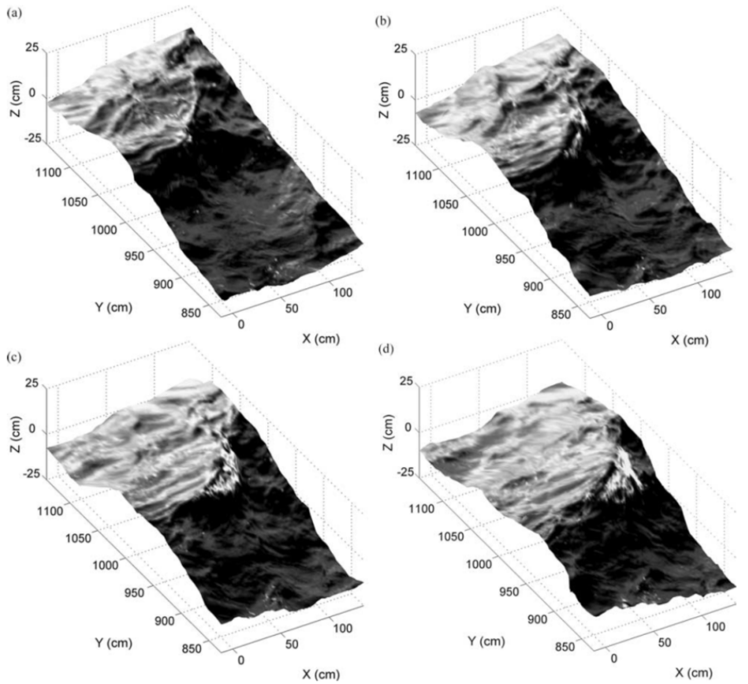
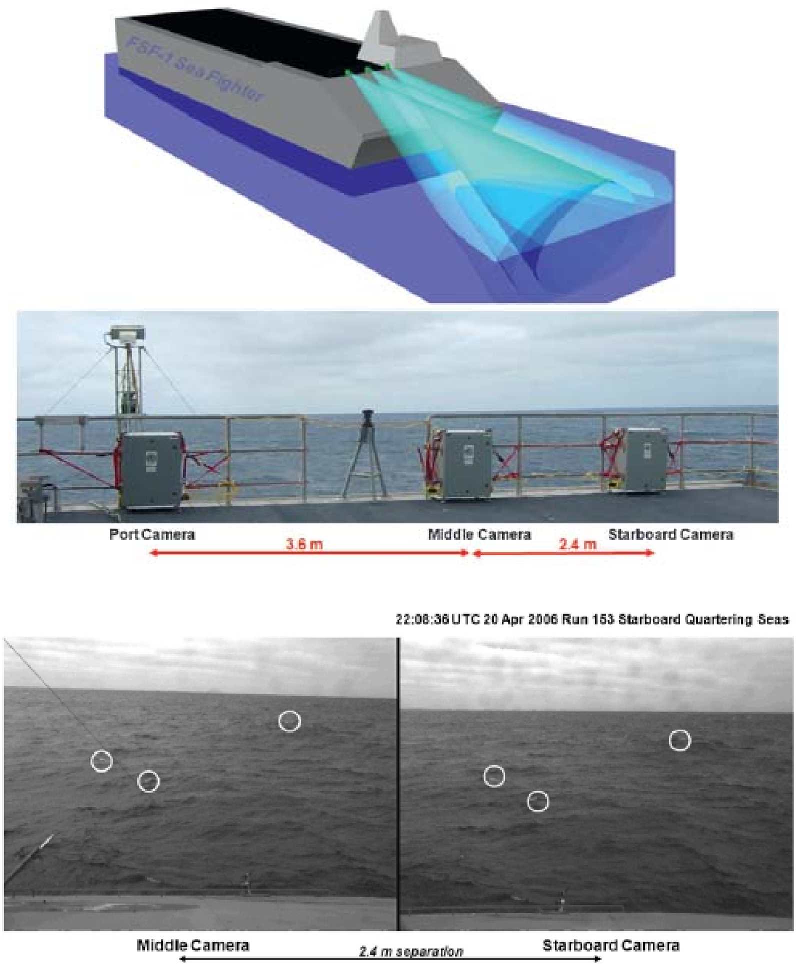
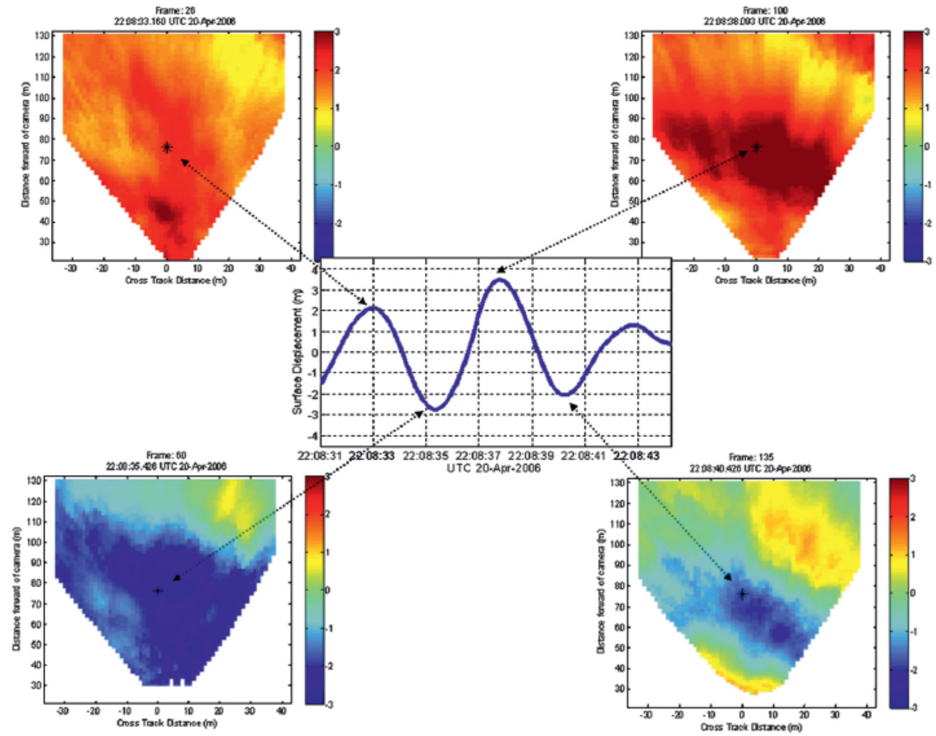


Fig. 9. A temporal evolution of a three dimensional wave breaking event at (a) $t = 0.0$ s, (b) $t = 0.1$ s, (c) $t = 0.2$ s, (d) $t = 0.3$ s, (e) $t = 0.4$ s, and (f) $t = 0.5$ s.

Literature review. Stereo systems

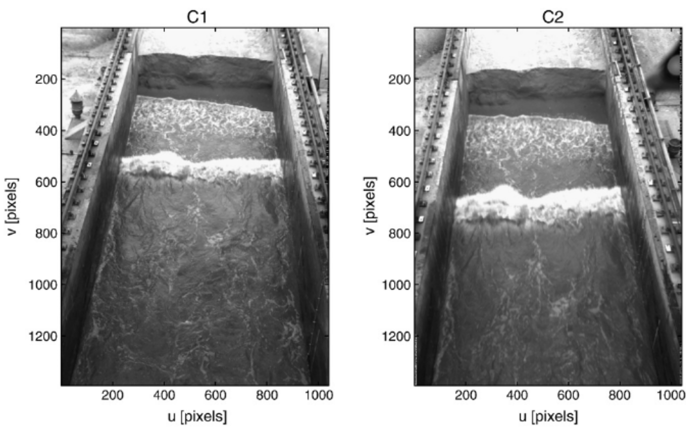
- Three-Dimensional Imaging of the High Sea-State Wave Field encompassing ship slamming events
  (Brandt et al 2010).





Literature review. Stereo systems

- Remote sensing of surf zone waves using stereo imaging
  (S. de Vries et al, 2011)



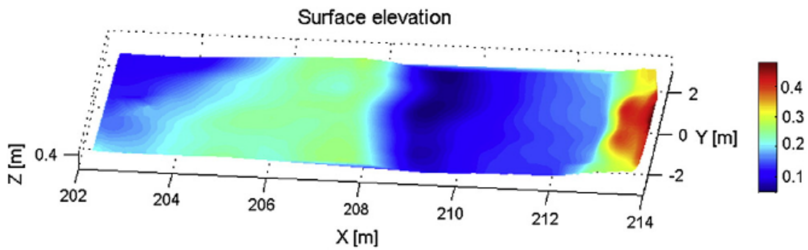


Fig. 12. Perspective view of the sample reconstruction of water surface elevation. Color contours denote elevation in meters.

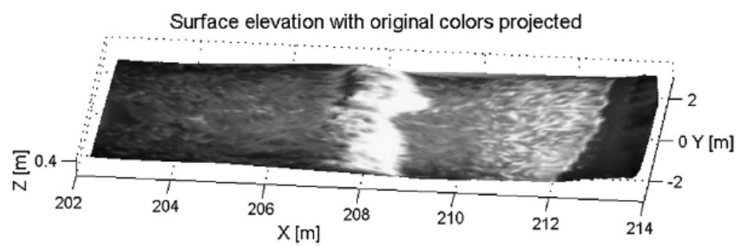
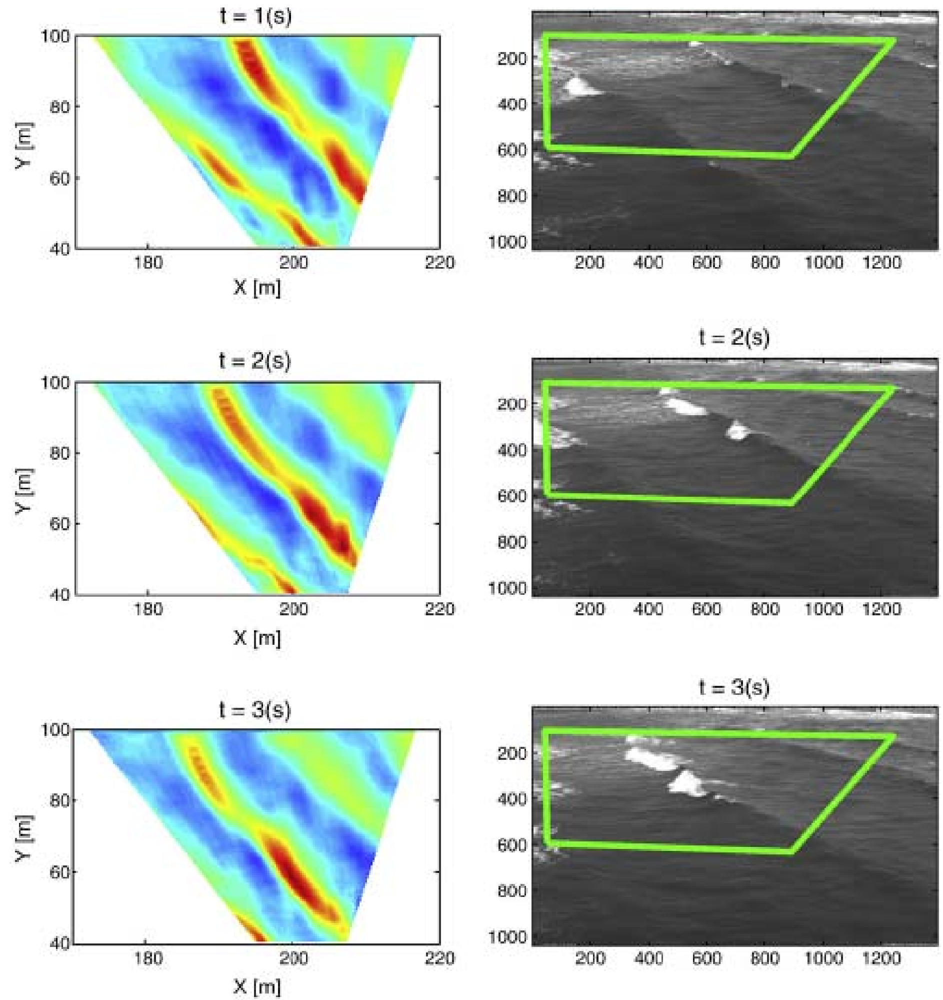
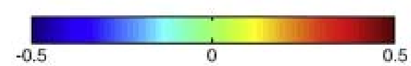


Fig. 13. Perspective view of original camera image mapped onto the three-dimensional water surface elevation.

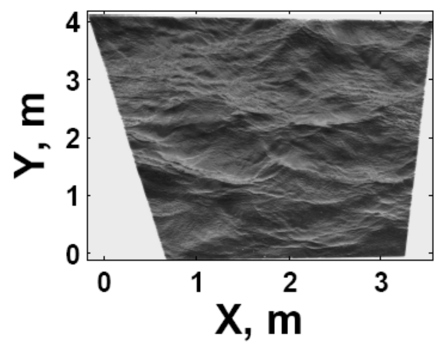


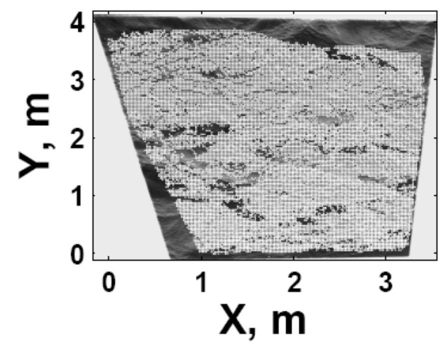


Literature review. Stereo systems

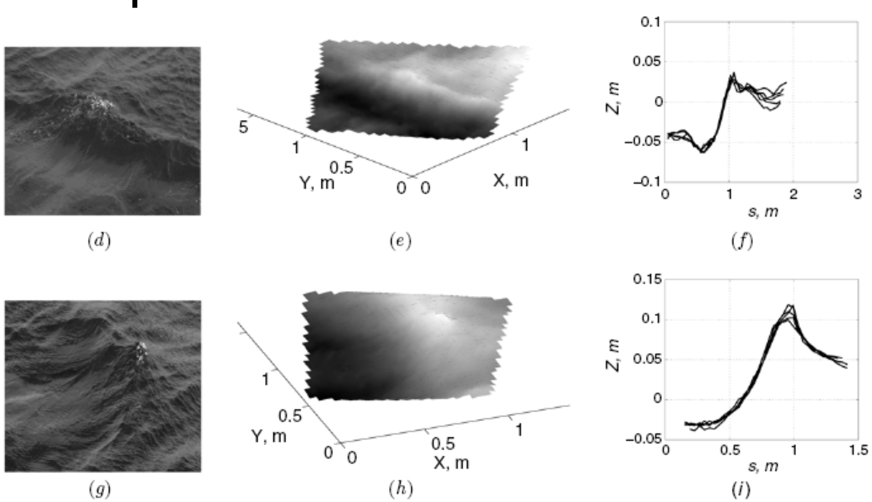
- Extraction of short wind wave spectra from stereo images
  (Kosnic and Dulov, 2011).
- Statistical characterization of short wind waves
  (Mironov, Kosnik, Dulov, Hauser, Guérin, 2012).

Problem: gaps (holes) in reconstructed surface

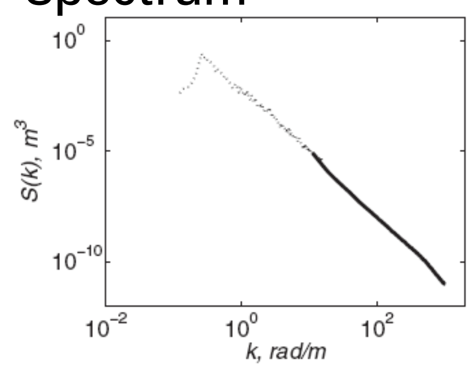




Sample reconstructions:



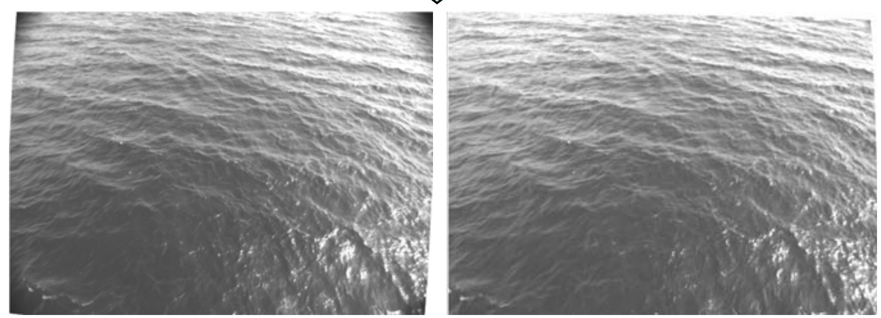
Spectrum



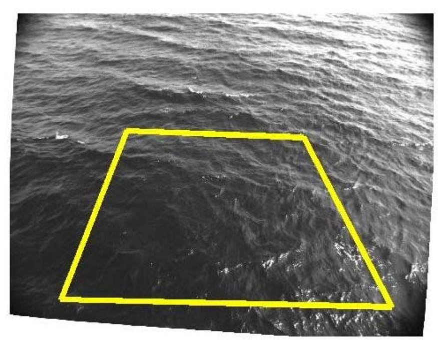
Reconstruction overview

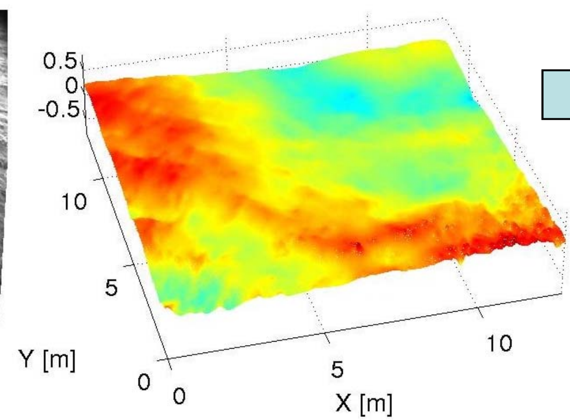
Platform: camera setup.
Acquisition system (storing, synchronization, calibration, etc.)

Acquired images



3D reconstruction of surface shape



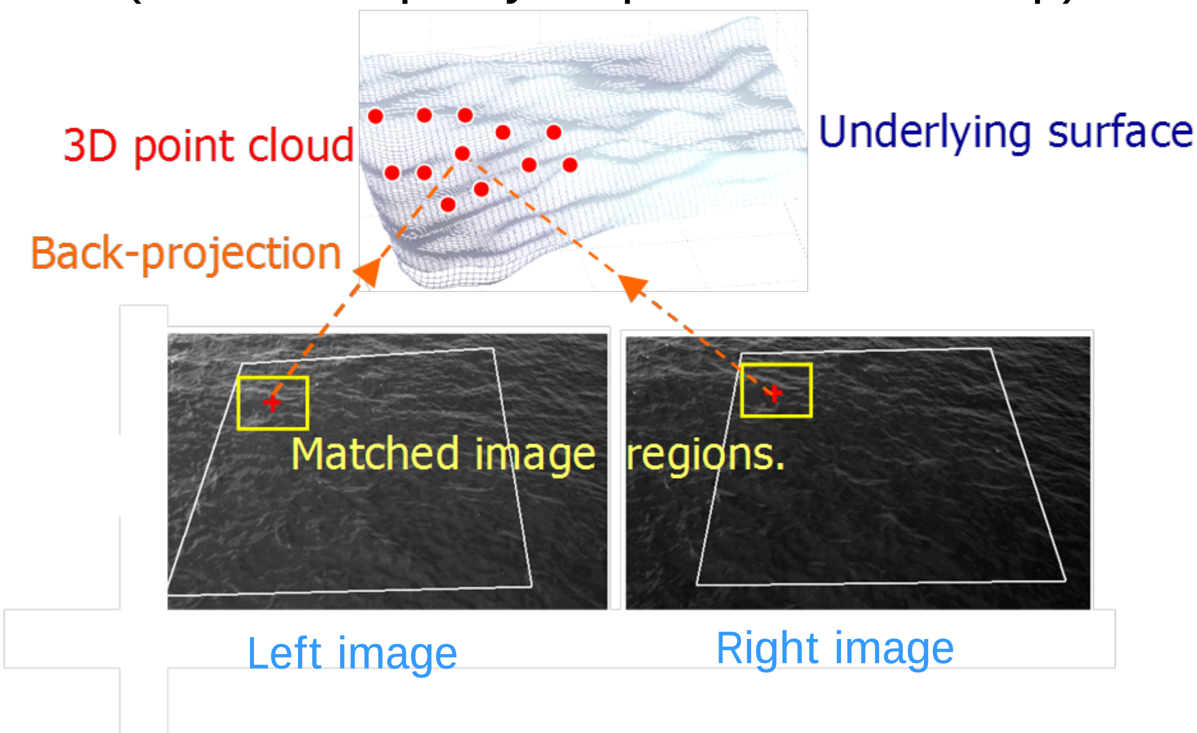


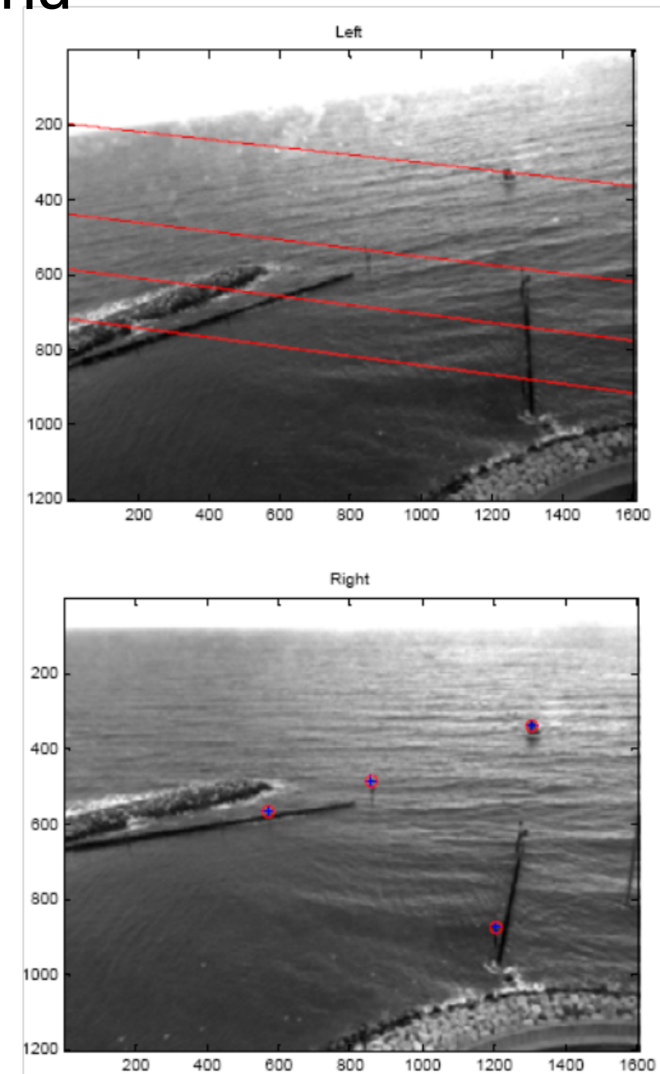
Data analysis (statistics, spectra)

Disparity map method

Steps:

1. Compute matching between images (disparity map)
2. Back-project matched points to 3-D world
3. Fit a surface through the points
   (convert disparity map to elevation map)





Disparity map method. Feature-based version

Some disadvantages:

- Sensitive to image noise.
- Correspondences are not easy to find.
- Unmatched regions: gaps in the surface.
- Requires strongly textured surfaces.
- Each point is treated independently (does not exploit continuity of surface).
- Post-processing is required.

How do we work around it?

Advantages of variational methods:

- Solid mathematical framework.
- Continuity of the wave surface in space & time:

  recovered points are not treated independently.
- Improve robustness: less sensitive to matching problems.
- Provide dense surface reconstructions.
- Allow controllability/priors on the unknowns.
- Imply less post-processing than classical methods.

Disparity map method. Variational version

Variational optimization approach to point matching:

– Cost functional: $E = E'_{\text{data}} + \alpha' E_{\text{smooth}}$, with

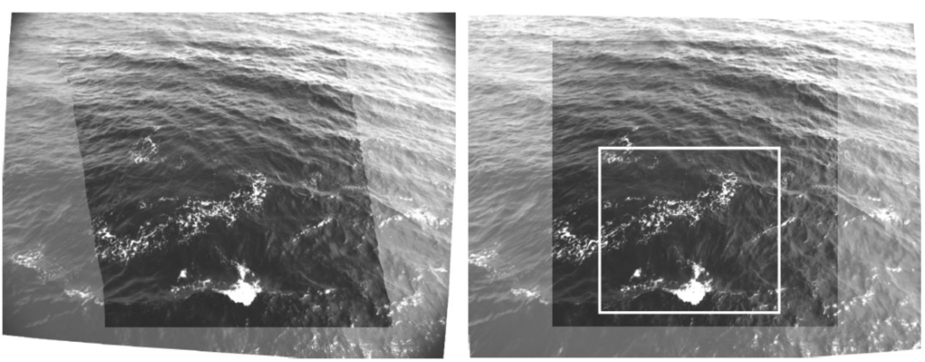
$$E'_{\text{data}}(\lambda) = \int_{\Omega} \frac{1}{2} \left(I_1(\mathbf{x}_1) - I_2(\mathbf{x}_2) \right)^2 d\mathbf{x}_1$$

$$E_{\text{smooth}}(\lambda) = \int_{\Omega} \frac{1}{2} \|\nabla \lambda\|^2 d\mathbf{x}_1$$

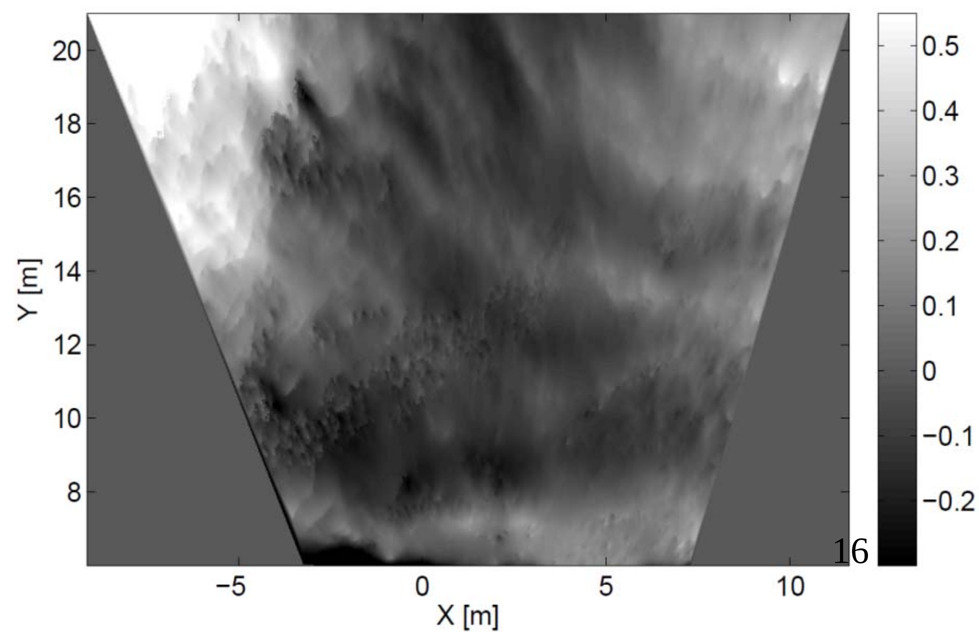
– Uknown: 2-D smooth disparity map.

Euler-Lagrange equations

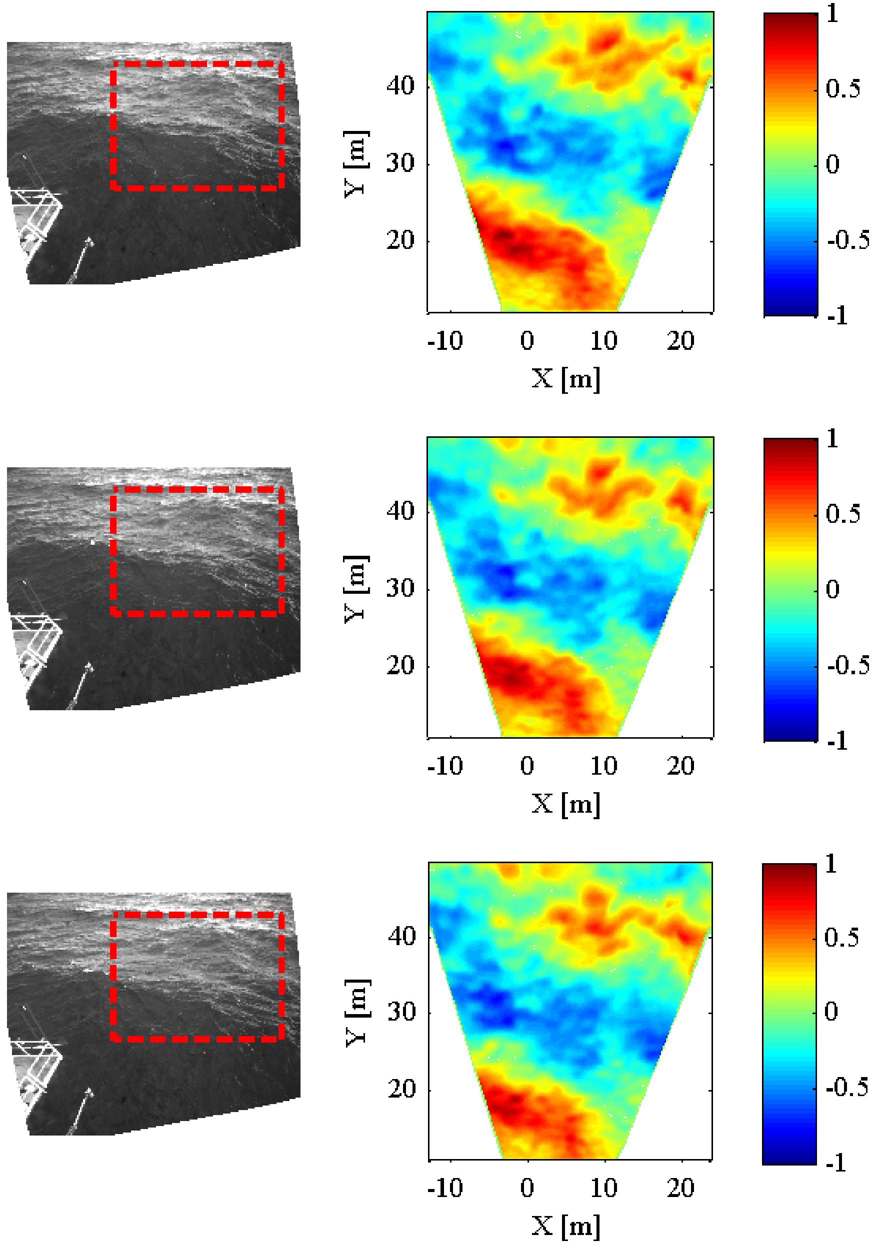
$$\alpha' \Delta \lambda + \left(I_1(\mathbf{x}_1) - I_2(\mathbf{x}_2) \right) \frac{\partial I_2(\mathbf{x}_2)}{\partial \lambda} = 0$$



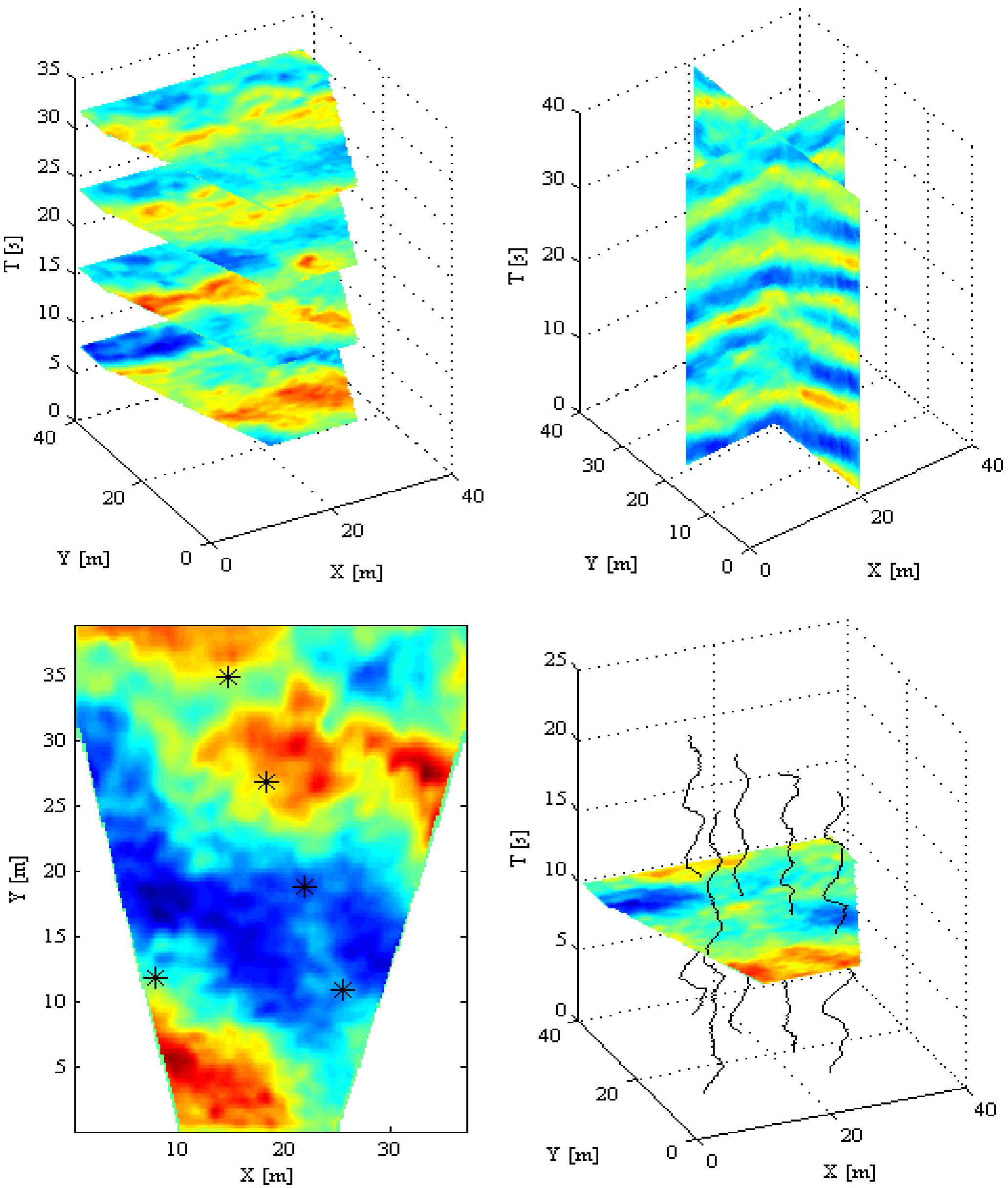
Elevation map after step 3



Disparity method. Sequential processing

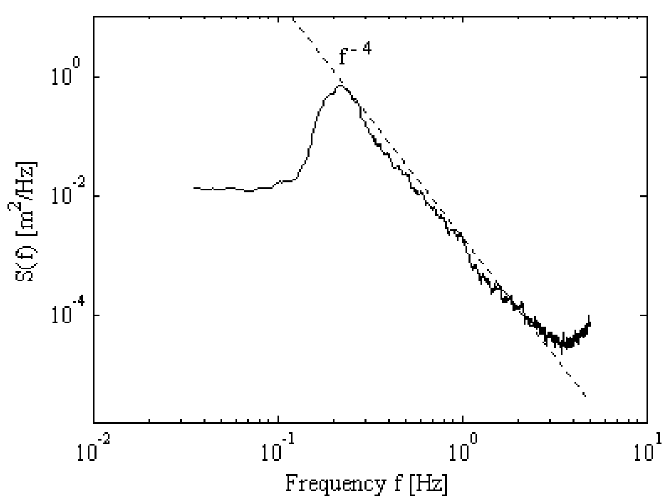


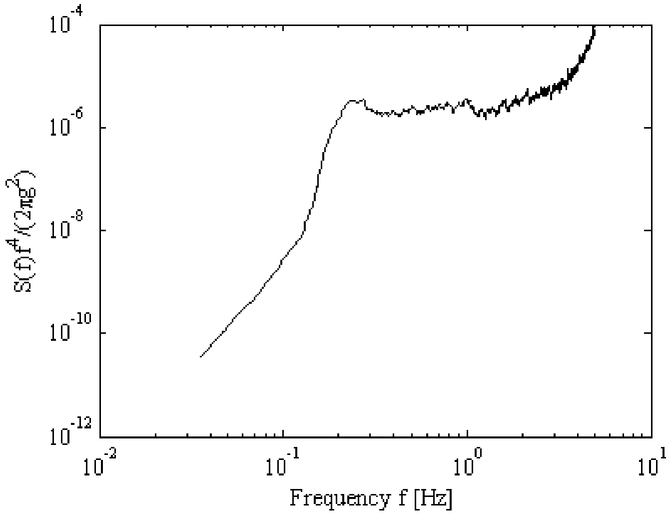
Disparity method. 4D space-time wave volume



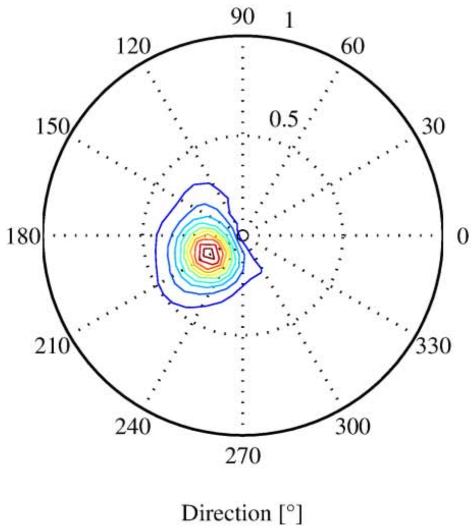
Disparity method. Data analysis. Spectra

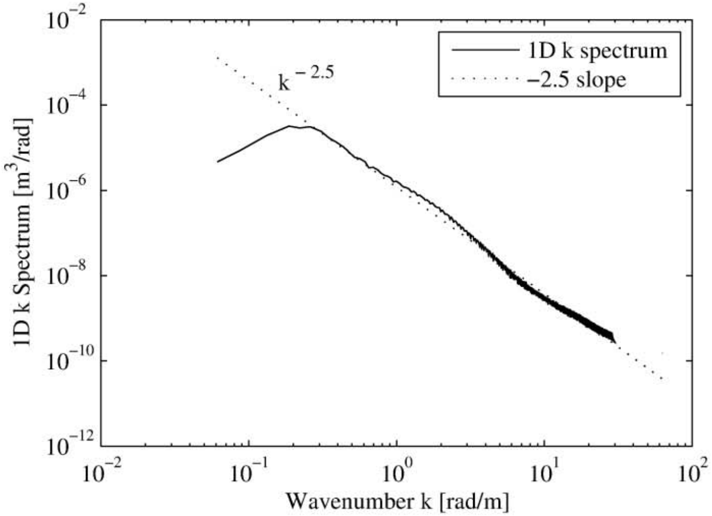
From time series at virtual probe points:





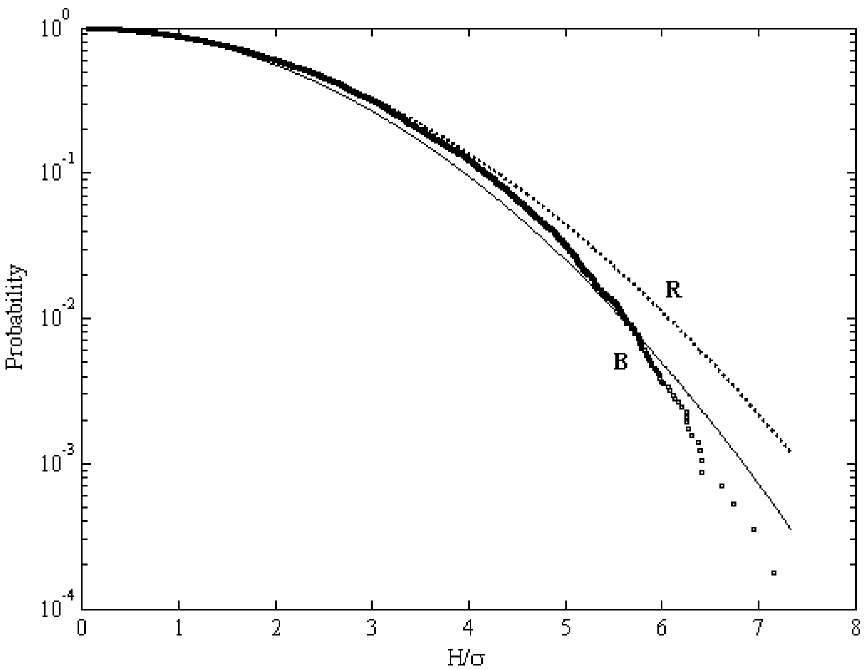
From 2-D snapshots. Directional and omni-directional spectra.



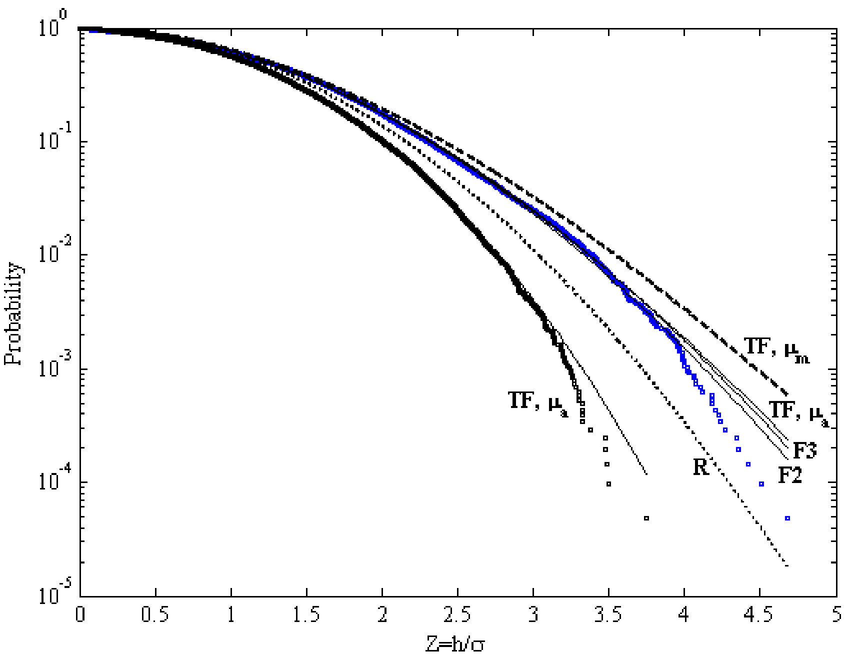


Disparity method. Data analysis. Statistics

Wave height exceedance probability.

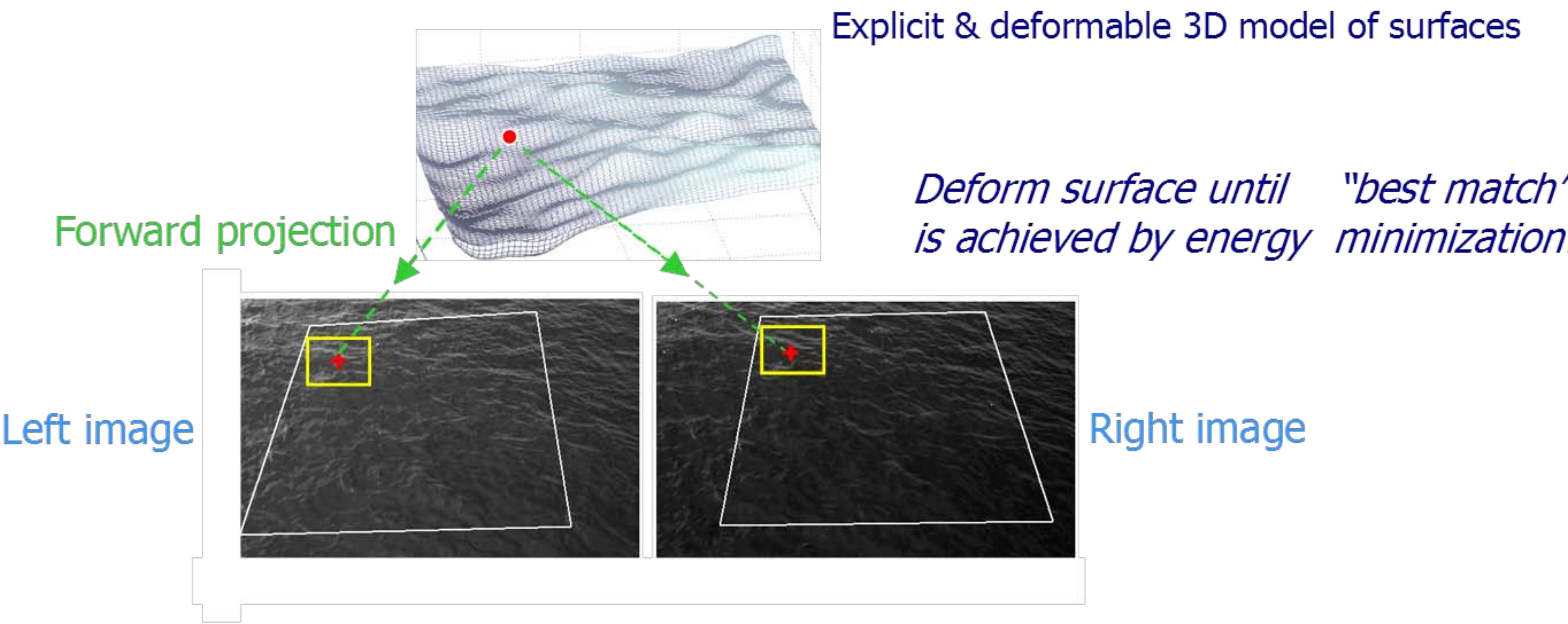


Wave crests and troughs exceedance probability



Elevation method

Strategy: adjust a 3D model to the 3D world represented by the data (images) so that an energy functional is minimized.



Elevation method

$$S(u,v) = (u, v, Z(u,v))$$

Design an Energy functional to be minimized

- Integral over the image domain (no derivatives of data = robust flow)
- Joint estimation of height Z(u,v) or the waves and its radiance f(u,v)

Energy: $E(S,f) = E_{\mathrm{data}}(S,f) + \alpha E_{\mathrm{geom}}(S) + \beta E_{\mathrm{rad}}(f), \qquad \alpha, \beta > 0.$

Data fidelity term: $E_{\mathrm{data}} = \sum_{i=1}^{N_c} E_i$ **where** $E_i = \int_{\Omega_i} \phi_i \, \mathrm{d}\mathbf{x}_i, \quad \phi_i = \frac{1}{2}\big(I_i(\mathbf{x}_i) - f(\mathbf{x}_i)\big)^2.$

Regularizers: $E_{\mathrm{geom}} = \int_U \frac{1}{2} \|\nabla Z(\mathbf{u})\|^2 \, \mathrm{d}\mathbf{u}, \quad E_{\mathrm{rad}} = \int_U \frac{1}{2} \|\nabla f(\mathbf{u})\|^2 \, \mathrm{d}\mathbf{u}.$

Recast the energy as a surface integral: $d\mathbf{x}_i = \frac{\det \mathtt{M}^i}{\tilde{Z}_i^3} (S - \mathbf{C}_i) \cdot \mathbf{N} \, dA$ **where depth is** $\tilde{Z}_i = \mathbf{n}_3^i \cdot (S - \mathbf{C}_i)$

Energy as a function of height and radiance

$$E(Z,f) = \int_U L(Z, Z_u, Z_v, f, f_u, f_v, u, v) \, \mathrm{d}\mathbf{u}.$$

Euler-Lagrange equations

$$\left[\begin{array}{rll} L_Z - (L_{Z_u})_u - (L_{Z_v})_v & = 0 & \text{in } U, \\ L_{Z_u}\nu^u + L_{Z_v}\nu^v & = 0 & \text{on } \partial U, \\ L_f - (L_{f_u})_u - (L_{f_v})_v & = 0 & \text{in } U, \\ L_{f_u}\nu^u + L_{f_v}\nu^v & = 0 & \text{on } \partial U. \end{array}\right.$$

Elevation method

Necessary optimality conditions:
System of coupled PDEs in height Z and radiance f of the surface.

$$
\left.
\begin{aligned}
g(Z,f) - \alpha \Delta Z &= 0 && \text{in } U, \\
b(Z,f) + \alpha \frac{\partial Z}{\partial \boldsymbol{\nu}} &= 0 && \text{on } \partial U, \\
-\sum_{i=1}^{N_c} (I_i - f)\mathrm{J}_i(Z) - \beta \Delta f &= 0 && \text{in } U, \\
\beta \frac{\partial f}{\partial \boldsymbol{\nu}} &= 0 && \text{on } \partial U,
\end{aligned}
\right\}
$$

Non-linear term (due to data-fidelity cost):

Focal length

Depth of point

Optical ray and Unit Normal

$$
g(Z,f) \;=\; \nabla f \cdot \sum_{i=1}^{N_c} |\mathtt{M}^i| \tilde{Z}_i^{-3} (I_i - f)(u - C_i^1, v - C_i^2),
$$

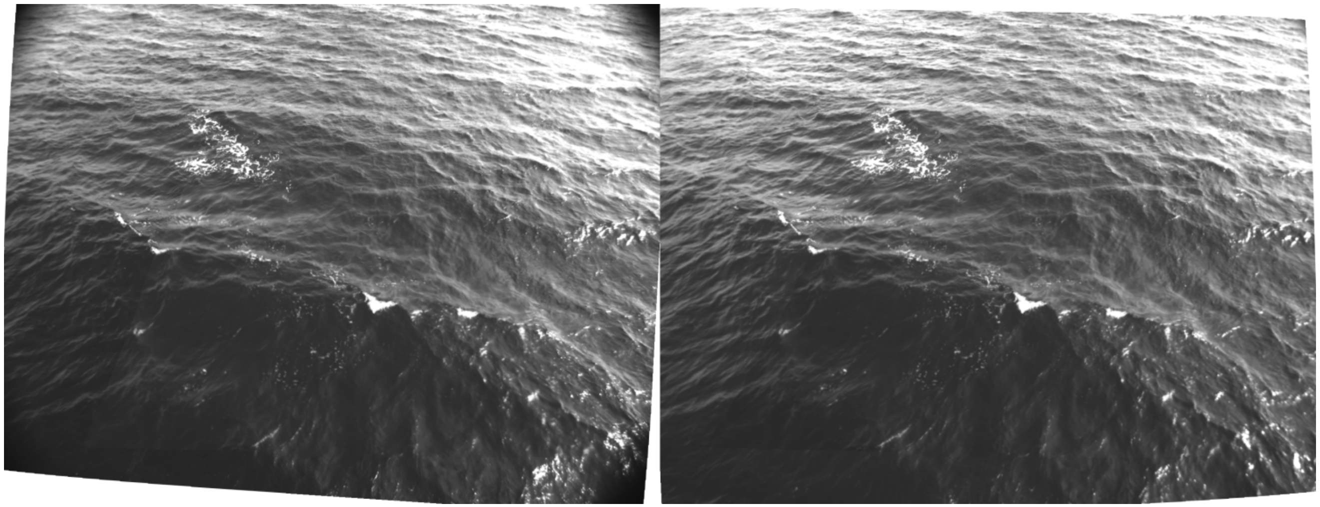
Radiance deriv

Photometric error

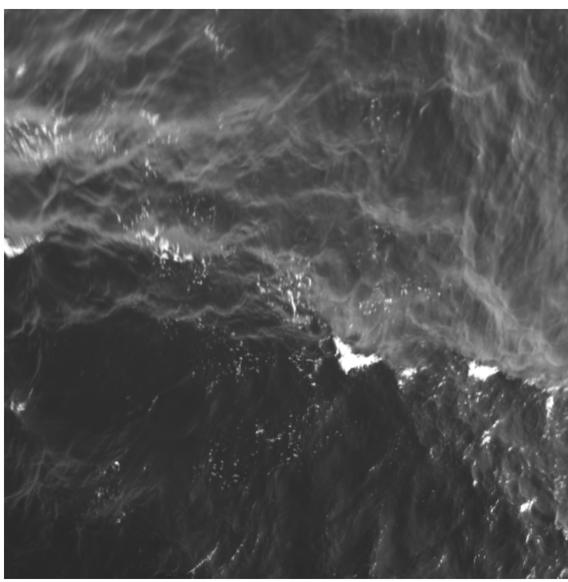
Multigrid solver: standard method for non-linear elliptic boundary value problems like this one.
Steepest descent method for the system of non-linear PDEs.

Elevation method (1 snapshot)

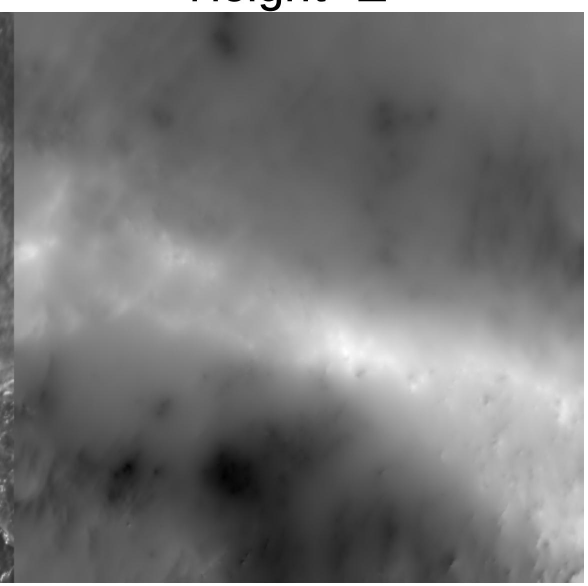
Modeled images



Radiance **f**

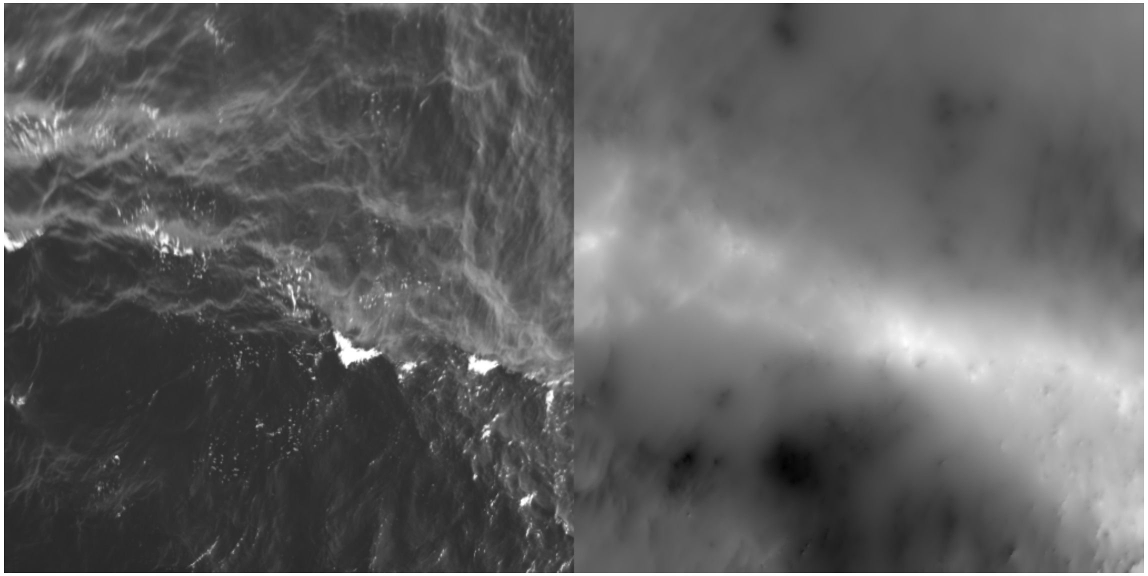


Height **Z**

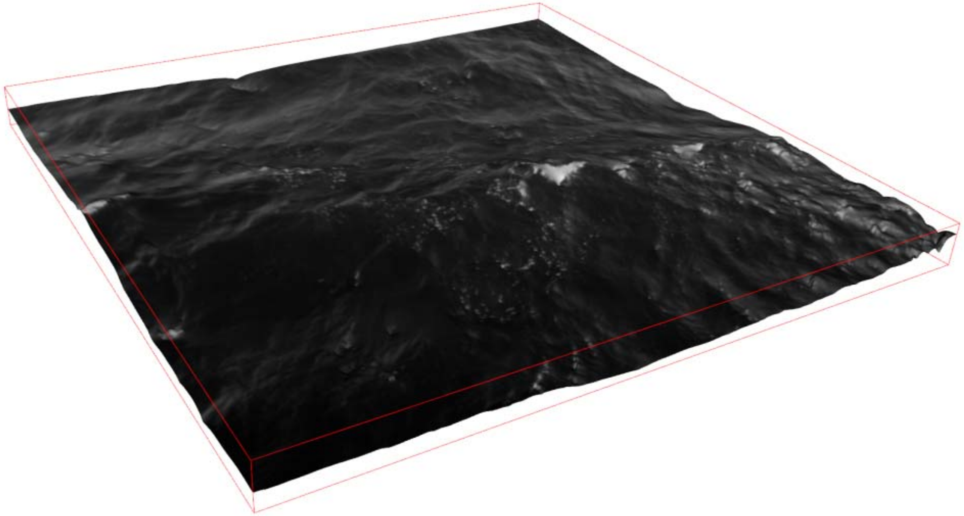


Elevation method (1 snapshot)

Radiance **f** Height **z**

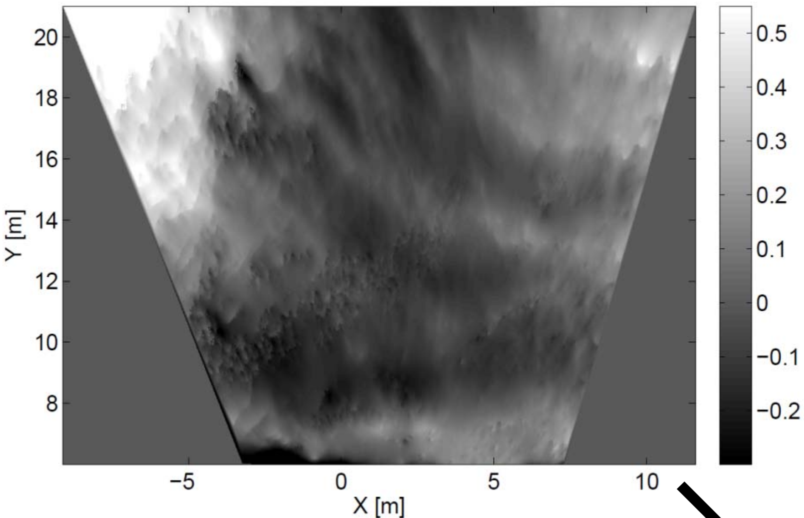


Reconstructed surface & texture

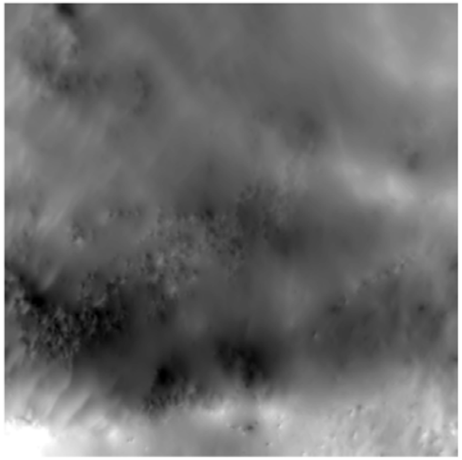


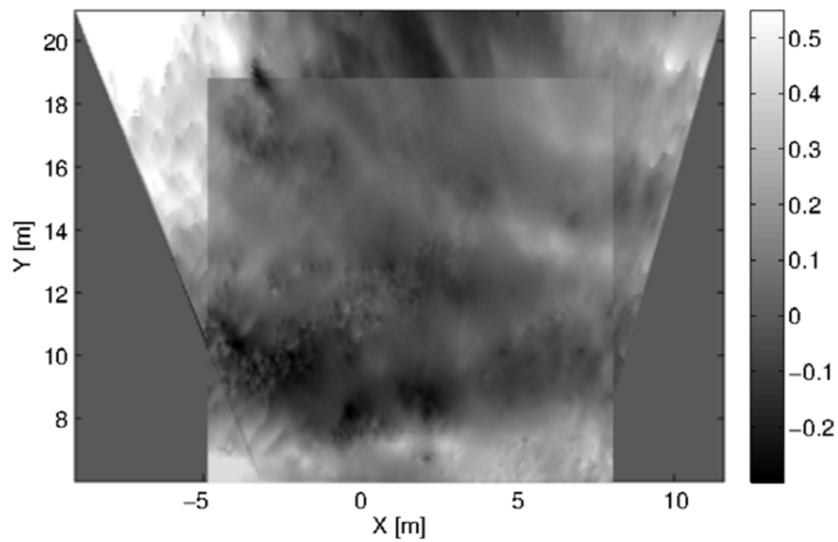
Comparison of estimated wave heights

Disparity method

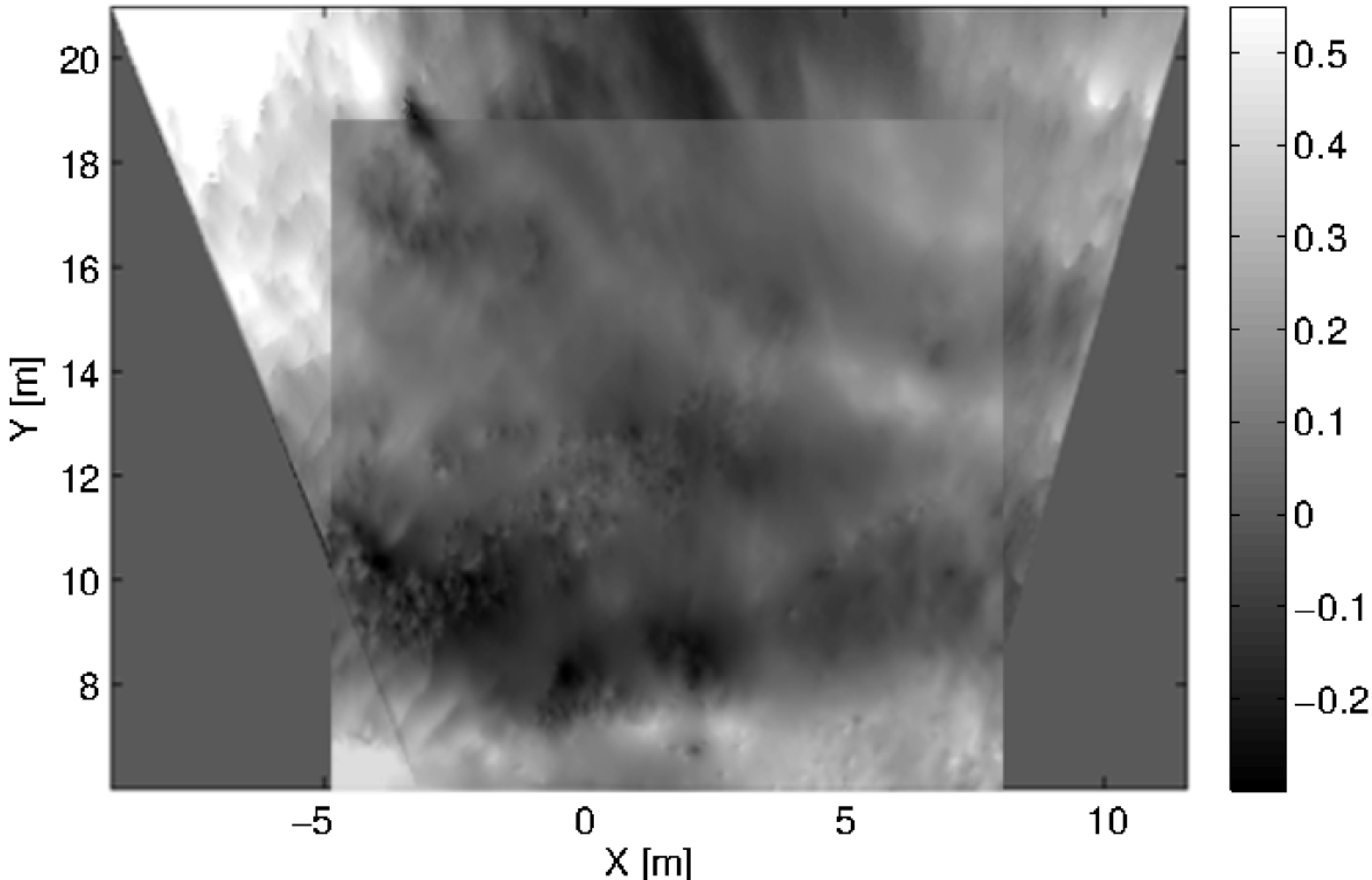


Elevation method

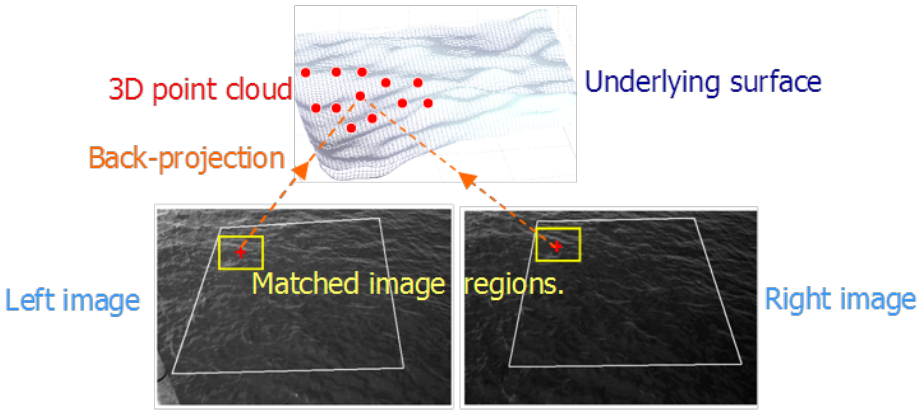




Comparison of estimated wave heights



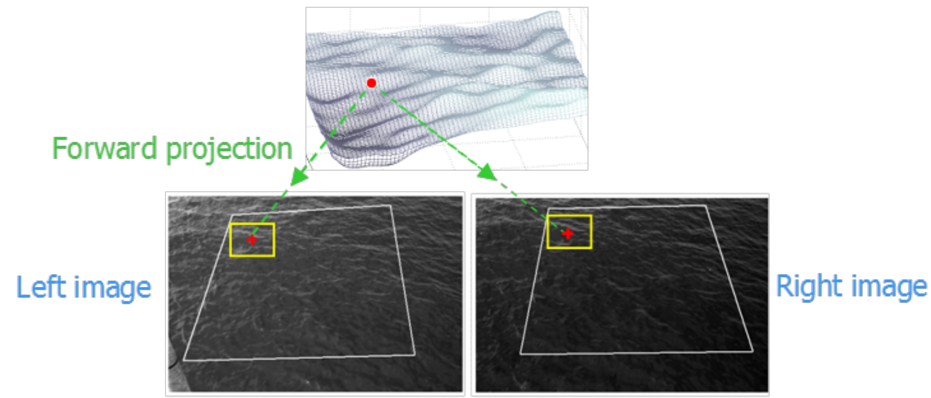
Disparity method



➢ **Differences:**

- Bottom-up approach: from pixels to surface
- Handle >2 images by pairs
- Requires triangulation + surface fitting.
- Does not take into account scene depth
- Does not take into account surface normal
- No radiance model: sensitive to noise
- Familiar, step-by-step.
- Single PDE in the unknown

Elevation method



➢ **Differences:**

- Top-bottom approach: from surface to pixels
- Easily handle more than 2 images
- No need to fit a surface through 3-D points
- Takes into account scene depth.
- Takes into account surface normal.
- Radiance model: less sensitive to noise
- Can incorporate physics of the waves.
- More mathematically involved: system of coupled PDEs.

Simultaneous snapshot reconstr. Time coherence

Data fidelity: measure photo-consistency througout the video for a candidate surface.
Regularizers: enforce spatial and temporal smoothness of the solution (disparity or height & radiance).

Disparity method

$$E'_{\text{data}}(\lambda) = \boxed{\int_T} \int_\Omega \frac{1}{2}\left(I_1(\mathbf{x}_1) - I_2(\mathbf{x}_2)\right)^2 d\mathbf{x}_1\, dt,$$

$$E_{\text{smooth}}(\lambda) = \boxed{\int_T} \int_\Omega \frac{1}{2}\|\nabla\lambda\|^2 d\mathbf{x}_1\, dt,$$

Elevation method

$$E_i(Z,f) = \boxed{\int_T} \int_{\Omega_i} \phi_i\, d\mathbf{x}_i\, dt,$$

$$E_{\text{geom}}(Z) = \boxed{\int_T} \int_U \frac{1}{2}\|\nabla Z\|^2 d\mathbf{u}\, dt,$$

$$E_{\text{rad}}(f) = \boxed{\int_T} \int_U \frac{1}{2}\|\nabla f\|^2 d\mathbf{u}\, dt,$$

Minimization approach:
- Obtain modified Euler-Lagrange eqs → set gradient descent eqs.
- Discretize and solve using 3-D multigrid methods.

Disparity method. Estimated wave height volume

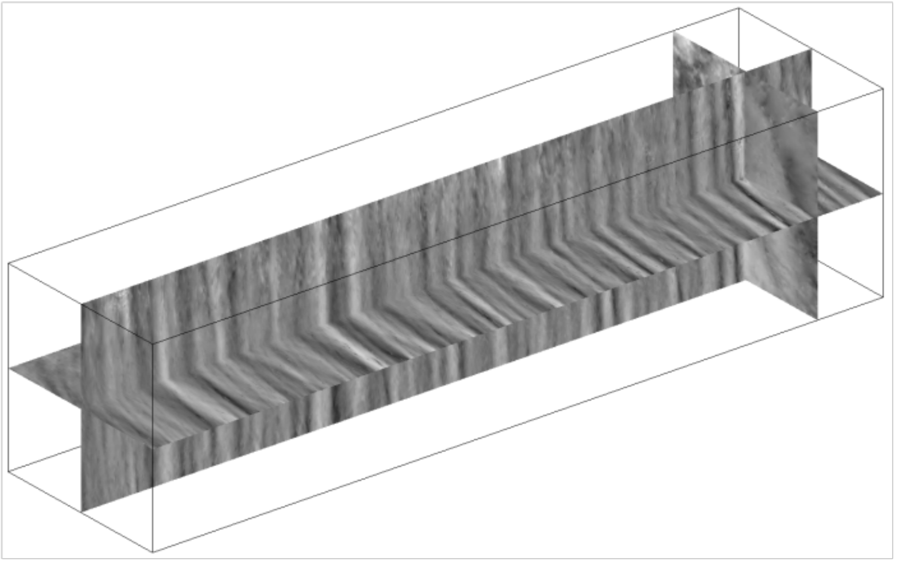
Input stereo video (2 cameras) at Crimean Platform:

- Input (subsampled) images: 406 x 309 pixels at 10 Hz frame rate.

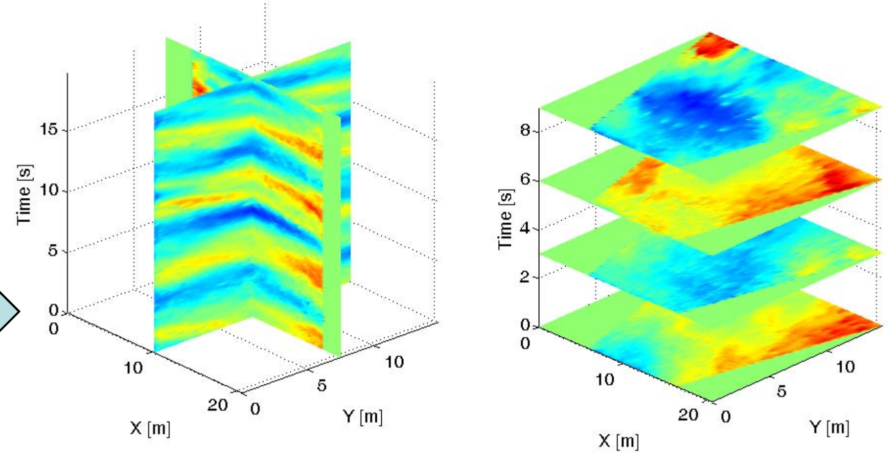
Reconstruction:

- Computational grid: 257 x 257 x 1025 points
- Resolution: 10 cm x 10 cm x 0.1 s
- Reconstructed area: 15 x 15 m^2 (inside trapezoid)
- #snapshots processed: 5125 (~8.5 min)

Disparity



Fitted height Z(x,y,t)



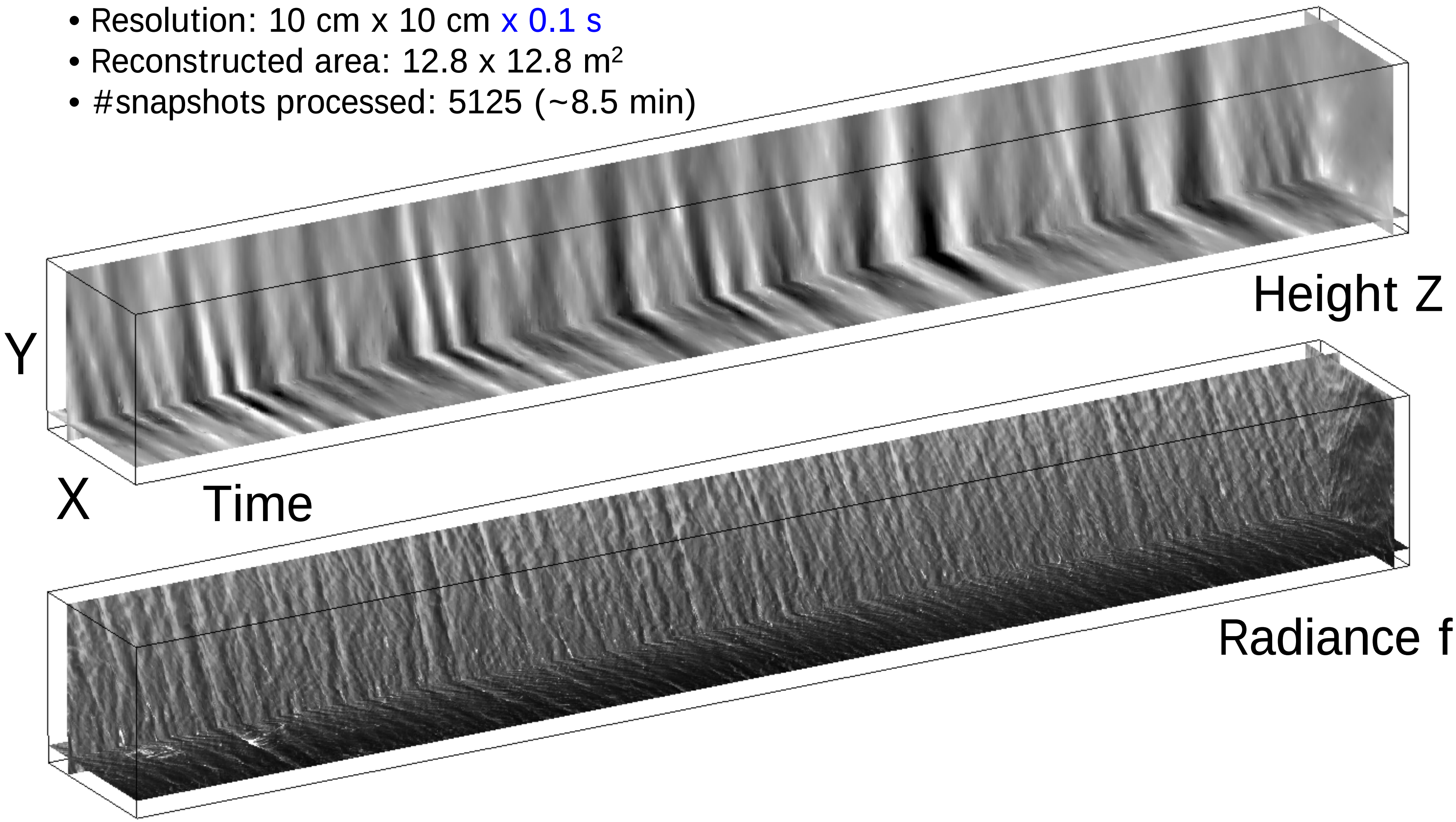
Elevation method. Estimated wave height volume

Input stereo video (2 cameras) at Crimean Platform:

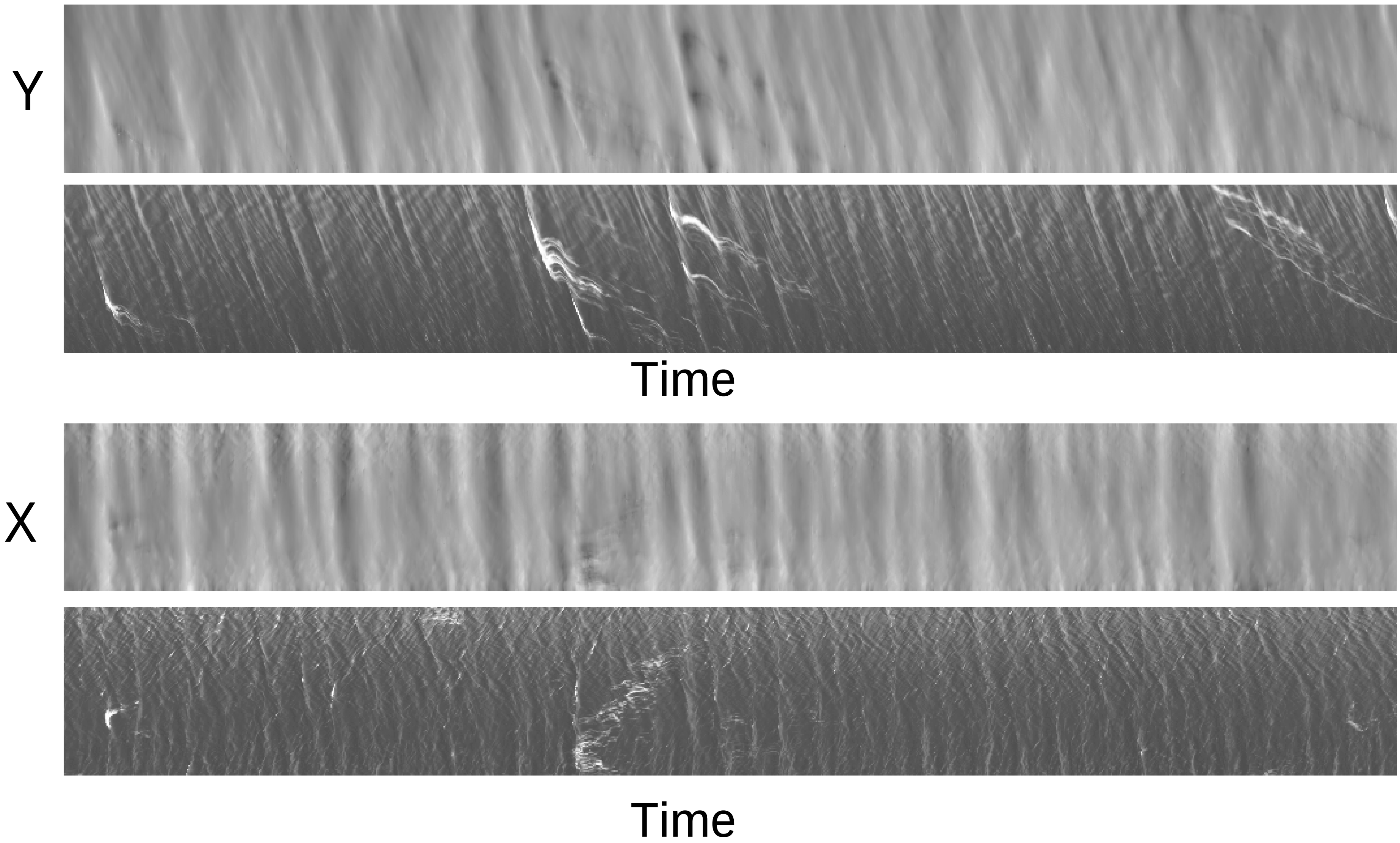
- Input (subsampled) images: 406 x 309 pixels at 10 Hz frame rate.

Reconstruction:

- Computational grid: 129 x 129 x 1025 points
- Resolution: 10 cm x 10 cm x 0.1 s
- Reconstructed area: 12.8 x 12.8 m^2
- #snapshots processed: 5125 (~8.5 min)

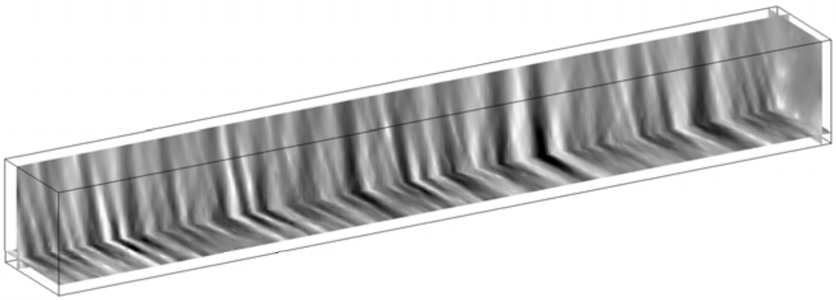


Elevation method. Estimated wave height volume

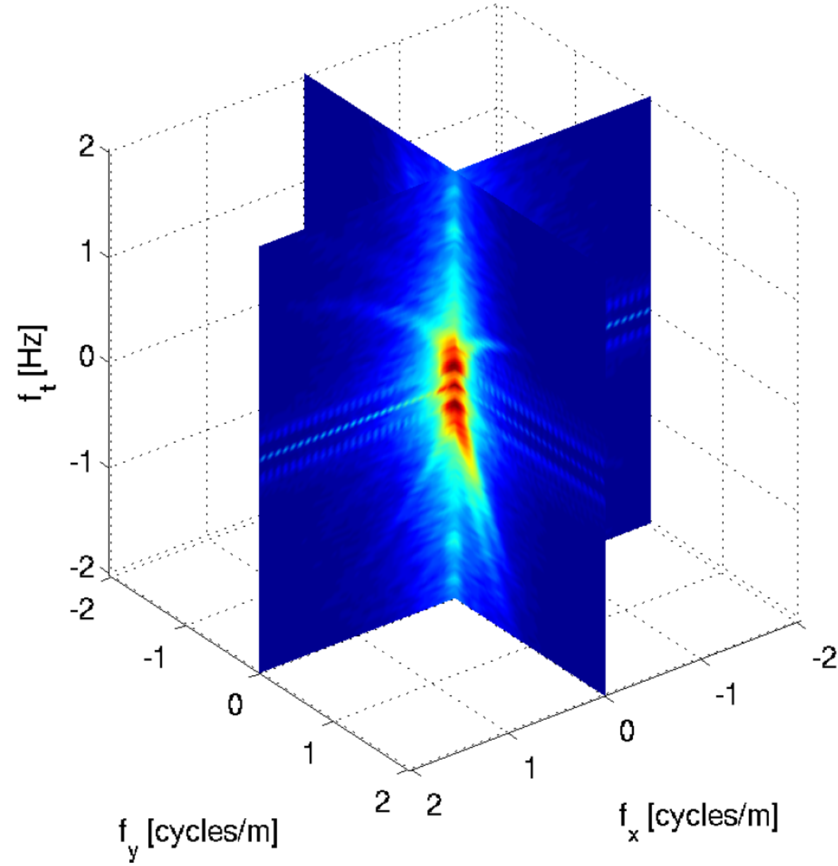


Estimated 3-D (power) spectrum

Wave height volume Z(x,y,t)



Fourier

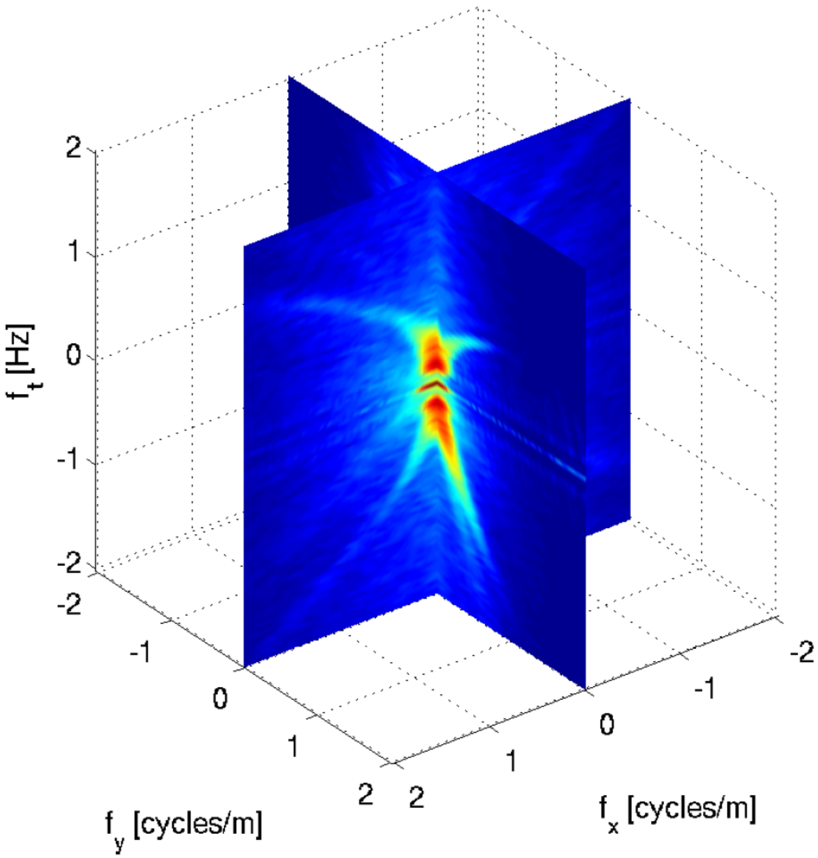


Crimea sequence. Input: 129x129x4100.

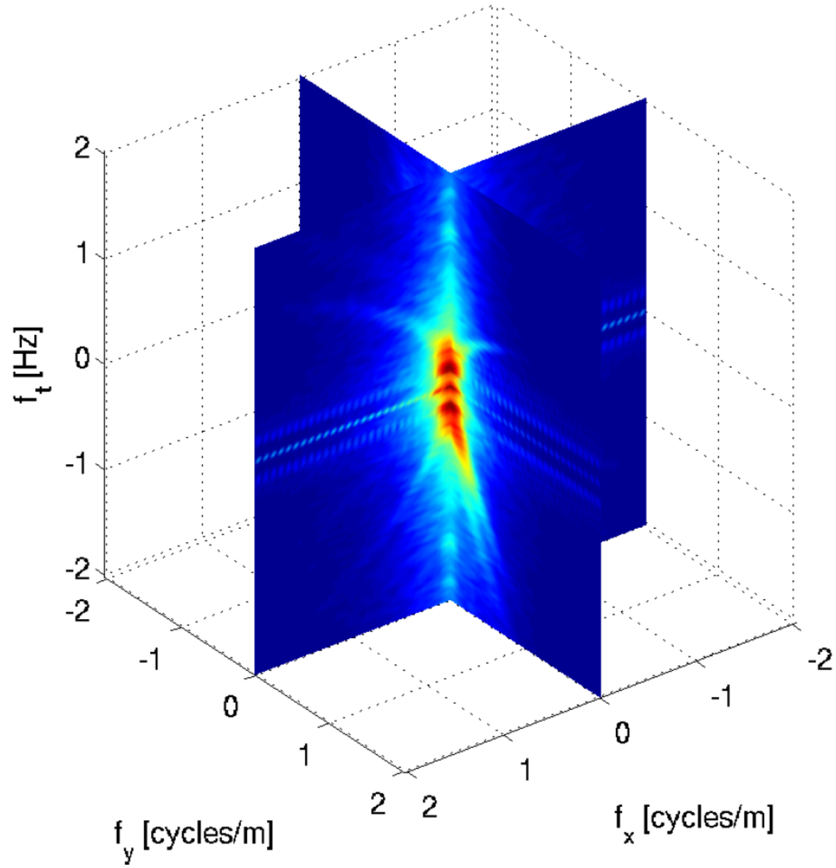
Output: 512x512x512

Estimated 3-D (power) spectrum

Disparity method



Elevation method

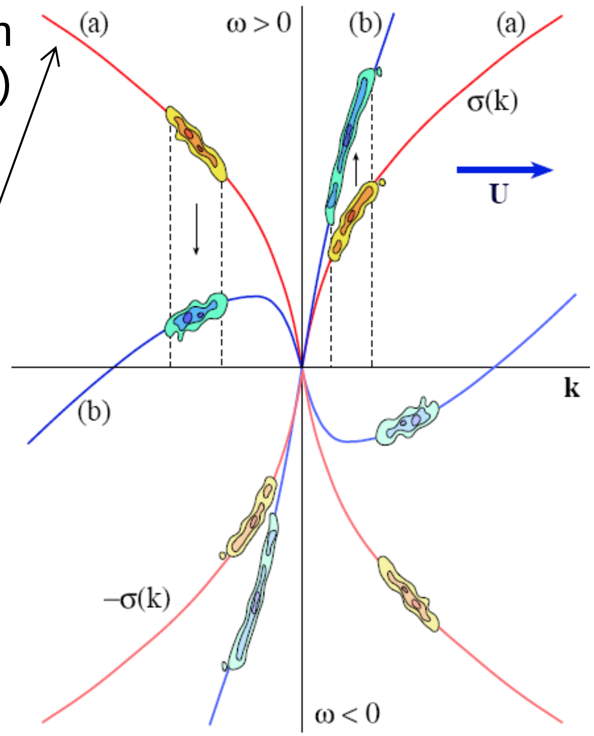


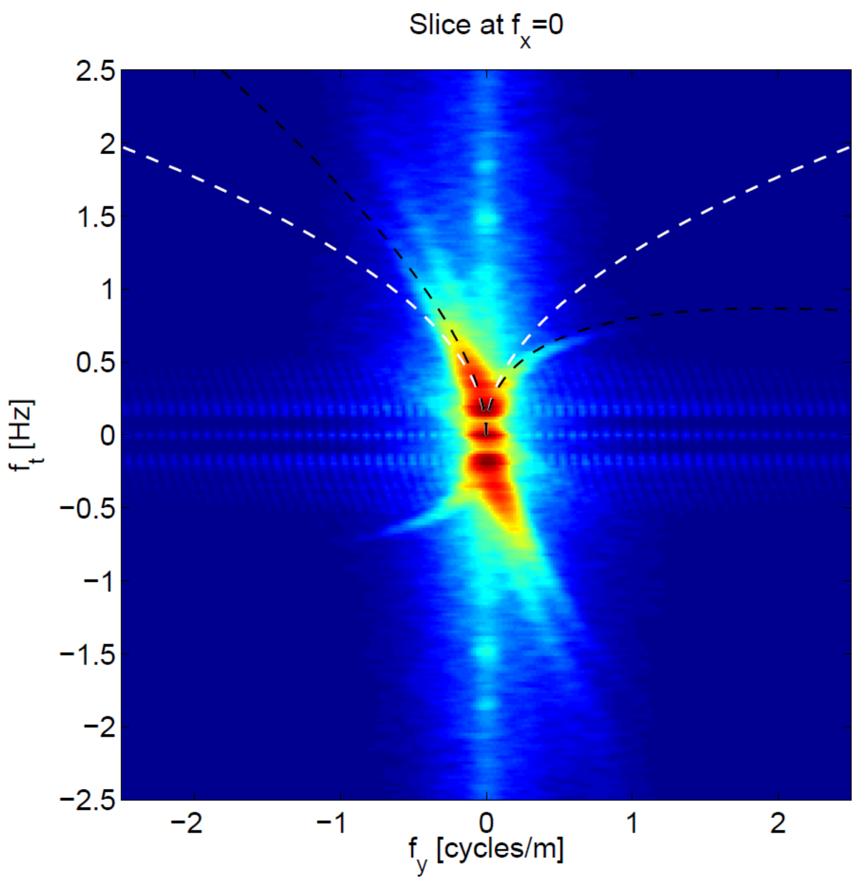
Slice of the 3-D spectrum

Taking into account the effect of surface currents:

Linear dispersion (in deep water)

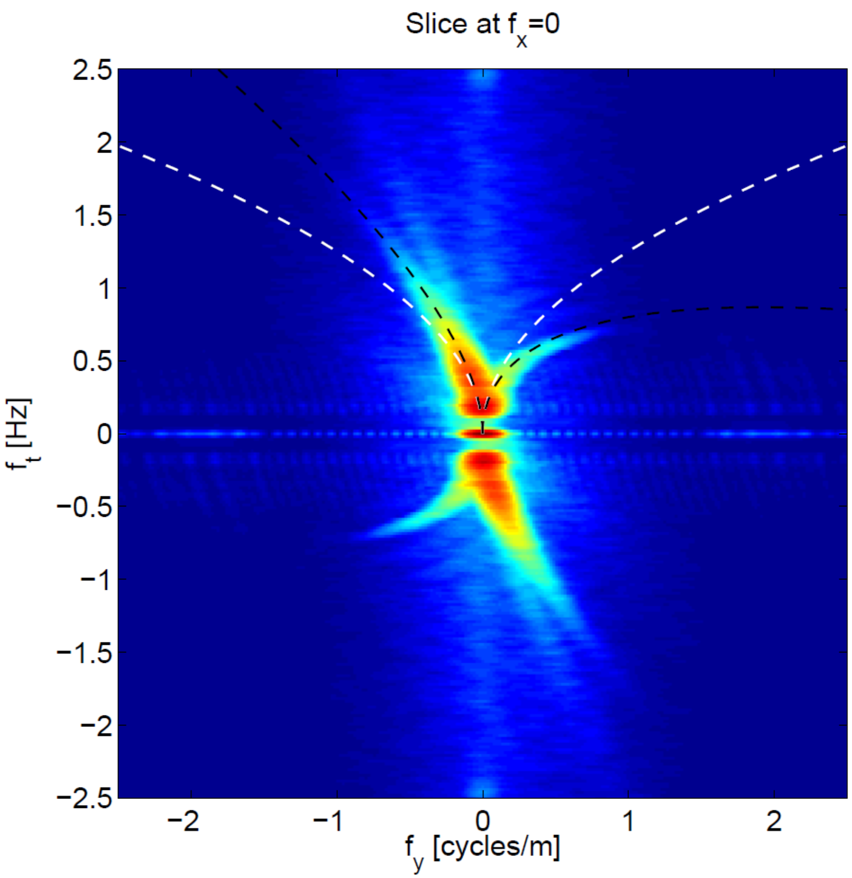
$$k = \frac{\omega^2}{g}$$



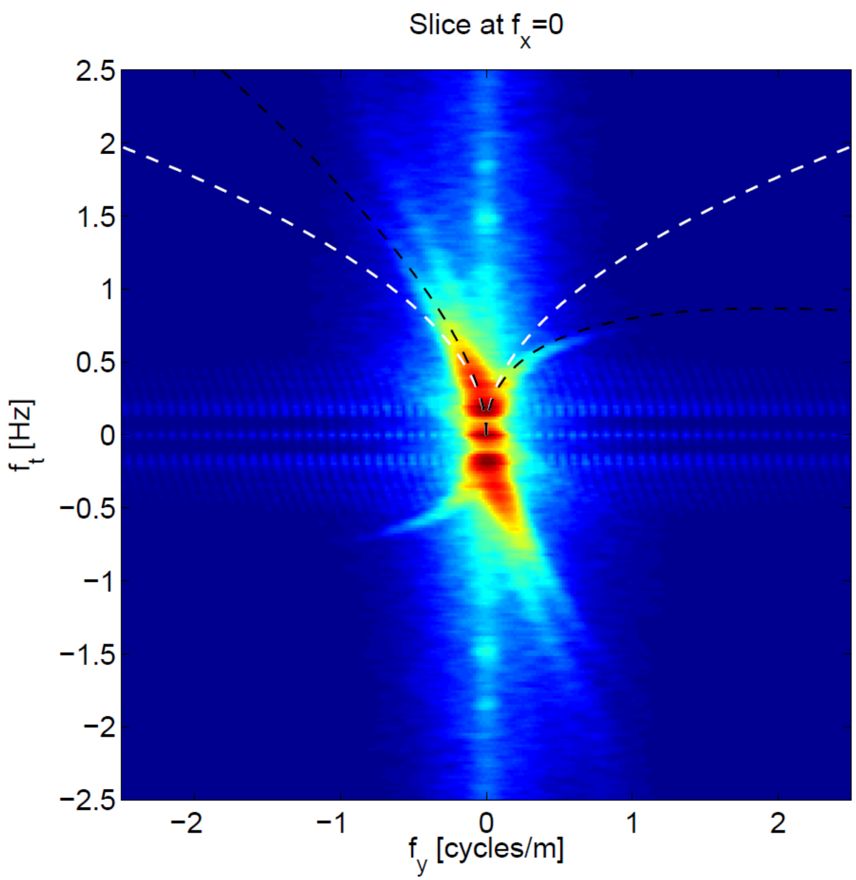


Slice of the 3-D spectrum

Disparity method

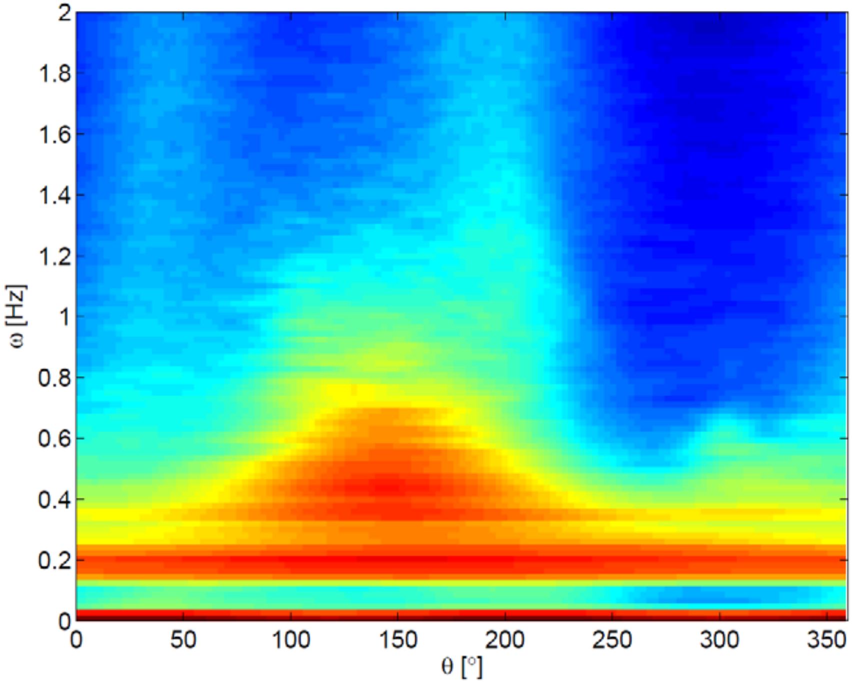


Elevation method

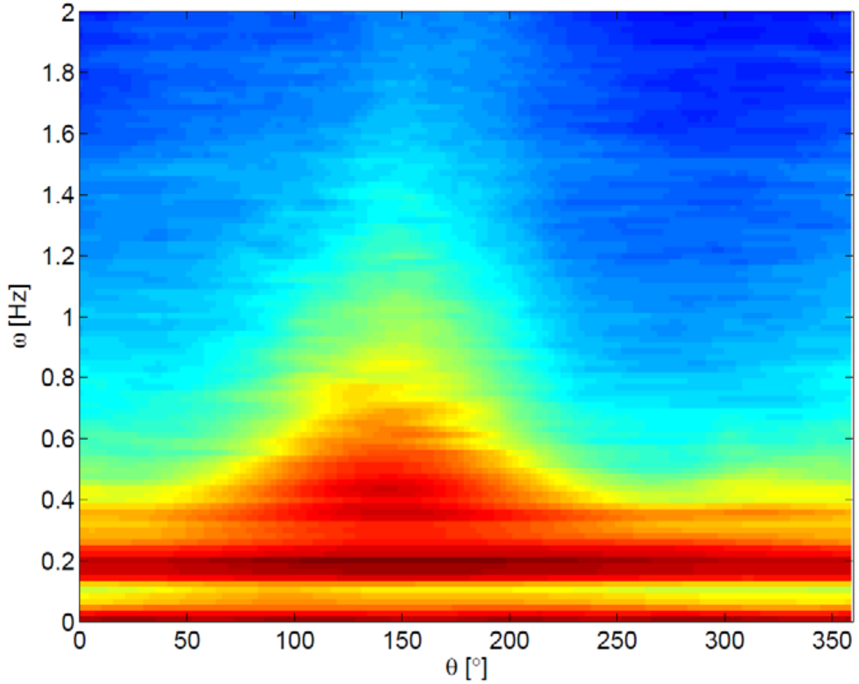


Directional Spectrum $F(\omega, \theta)$

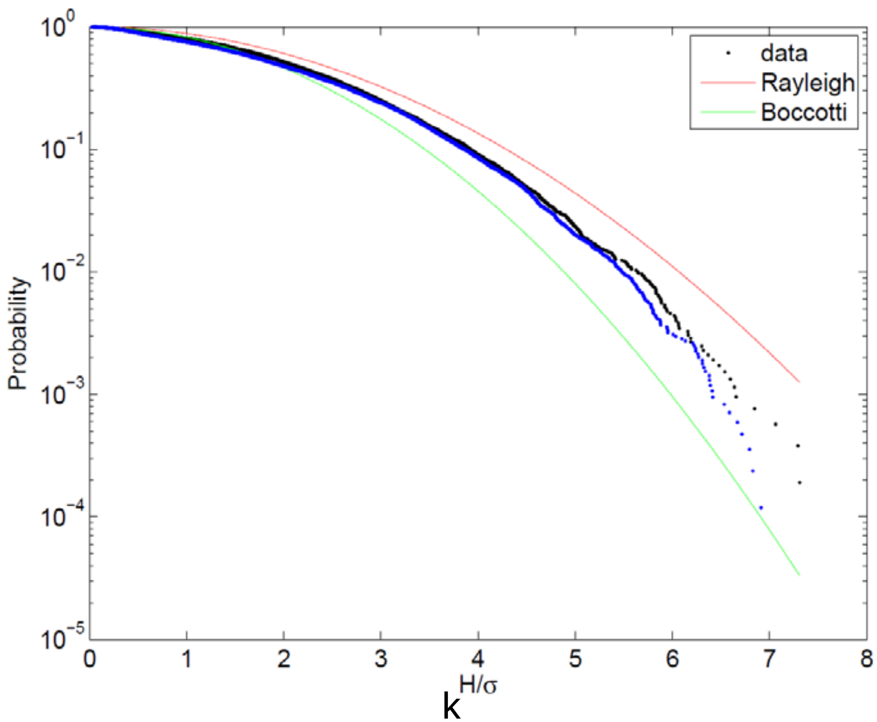
Disparity method



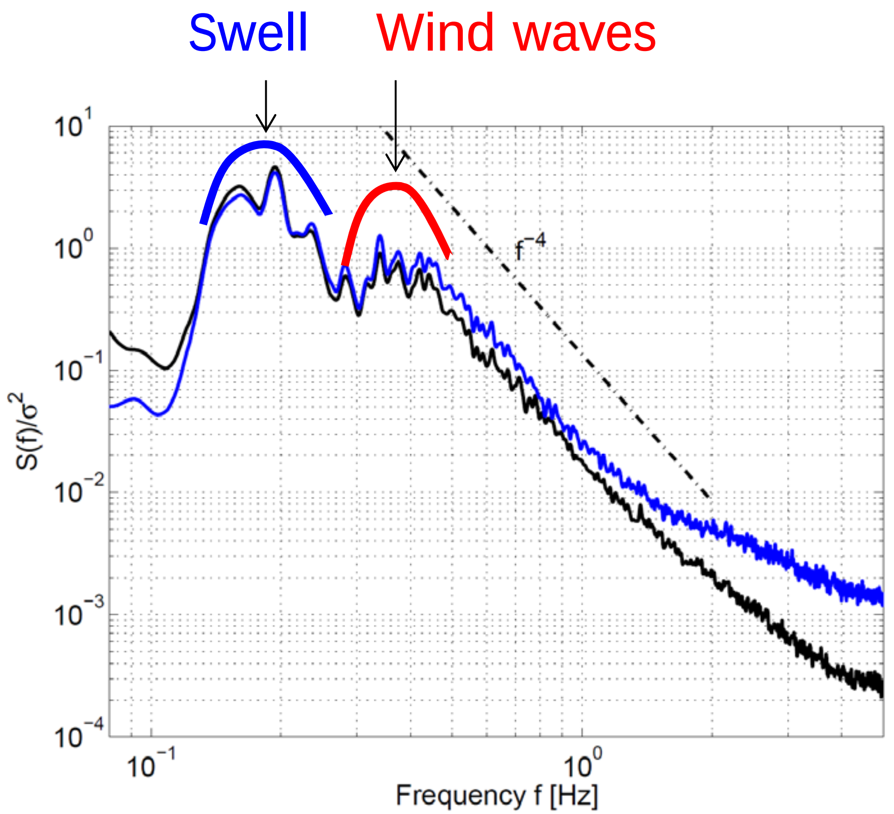
Elevation method



Analysis of time series at virtual probes.



Wave height exceedance probability.
(disparity method)



Normalized frequency spectrum.
disparity method & **elevation method**

Applications

- Wave measurements: Hs, Tp, Tm, etc.
- Comparison of theoretical models with real data.
- Statistical analysis: expected maximum wave height over an area (for the design of offshore structures), etc.
- Spectral measurements: estimation of currents, measure slope of tail of the spectrum, etc.

Conclusions

- Stereo reconstruction methods...
  - have more advantages than classical wave measurements (area vs. point measurements).
  - provide reliable statistics and accurate predictions of ocean waves due to the rich information content of video data.

- Comparison of variational approaches:
  - Both provide dense wave height field estimations and allow to enforce continuity in space & time.
  - Different strategies, but similar results.
  - Elevation method is slightly better since it takes into account surface normal & depth.

- Disadvantages: computational cost (but feasible).

Future work

- Theoretical improvements:
  - Physics-based energy regularizer: the wave equation.
  - Filtering via POD / DMD (wave height analysis).

- Computational considerations:
  - Parallel-processing via GPU.
  - Preconditioned Conjugate Gradient on linearized system.

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- G. Gallego, A. Yezzi, F. Fedele, A. Benetazzo. Variational stereo imaging of oceanic waves with statistical constraints. **IEEE Trans. Image Processing**, 22(11):4211-4223, 2013.
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- A. Benetazzo, F. Fedele, G. Gallego, P.-C. Shih, A. Yezzi, Offshore stereo measurements of gravity waves, **Coastal Engineering**, 64:127-138, 2012.
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Acknowledgements:

THANK YOU FOR YOUR ATTENTION.

ANY QUESTIONS ?

More information:

http://www.gti.ssr.upm.es/~ggb/

http://savannah.gatech.edu/people/ffedele/Research/